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Integrating a Strategic Sustainable Development Perspective in Product-Service System Innovation

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Doctoral Dissertation in
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Tony

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Abstract

There is an intersection where society's social and ecological challenges coincide with the industrial firm's challenge to maintain profitability in a globalizing world. Products connect these challenges. The development of these products together with services (product-service systems) therefore provides a critical intervention point to address these challenges. This includes e.g. defining what the products and services are, how they will deliver value to users, and the business models that enable them to be realized, as well as how these can contribute to sustainable development of society.

The overarching goal of this research is to contribute to sustainable development of society by better understanding how a strategic sustainable development perspective based on backcasting from basic principles for a sustainable society can be brought into and guide product-service system innovation. Interviews with industry professionals, workshops with both manufacturing companies and within student projects, and industrial cases studies, together with a review of literature and theoretical considerations, provide the methodological basis for this work.

This thesis contributes to clarifying theoretical and practical possibilities and limitations for a strategic sustainable development perspective to guide product-service system innovation and provides a basis for the integration of these concepts. The findings indicate that the co-innovation of products and services in product-service systems can contribute to sustainable development of society both by supporting reduced material and energy use and by supporting improved life cycle management of materials. Further, a strategic sustainable development perspective can contribute to the refinement of existing tools and methods in product-service system innovation by providing an operational definition of sustainability articulated in the form of first-order principles that describe the boundary conditions for a sustainable society, and by providing guidelines for how to approach a vision of success inside those boundaries in a strategic way.

In order to identify solutions that meet society's pressing challenges, new solution spaces may need to be identified, and this can be enabled by a shift from product development with service as "add-ons" to their co-innovation in product-service systems. An initial approach for how this could be enabled through bringing together set-based approaches to design product-service systems with a strategic sustainable development perspective is presented.

Keywords

sustainable product innovation, sustainable product development, strategic sustainable development, product-service systems (PSS), life cycle management, set-based product development.

Thesis Disposition

This thesis includes an introduction and the following six papers, which have been slightly reformatted from their original publication. Their content, though, is unchanged.

Paper A

Thompson, A.W., P. Lindahl, S. Hallstedt, H. Ny and G. Broman. 2011. Decision Support Tools for Sustainable Product Innovation in a few Swedish Companies. *3rd International Conference on Research into Design (ICoRD)*. Centre for Product Design and Manufacturing. Bangalore, India.

Paper B

Hallstedt, S., A.W. Thompson and P. Lindahl. Key Elements for Implementing a Strategic Sustainability Perspective in the Product Innovation Process. *Journal of Cleaner Production*. Accepted for publication.

Paper C

Thompson, A.W., T.C. Larsson and G. Broman. 2011. Towards Sustainability-driven Innovation through Product-Service Systems. *3rd CIRP International Conference on Industrial Product-Service System (IPS2)*. The International Academy for Product Engineering (CIRP). Braunschweig, Germany.

Paper D

Thompson, A.W., H. Ny, P. Lindahl, G. Broman and M. Severinsson. 2010. Benefits of a Product Service System Approach for Long-life Products: The Case of Light Tubes. *2nd CIRP International Conference on Industrial Product-Service System (IPS2)*. The International Academy for Product Engineering (CIRP). Linköping, Sweden.

Paper E

Thompson, A.W., T.C. Larsson, O. Isaksson and G. Broman. Pursuing Sustainability through Servitization in Manufacturing Firms. *Journal of Cleaner Production*. Submitted.

Paper F

Thompson, A. W., S. Hallstedt, and O. Isaksson. 2012. Introductory Approach for Sustainability Integration in Conceptual Design. *International Design Conference (Design 2012)*. Dubrovnik, Croatia.

Related Work

Below is a list of related work published during the period of Ph.D. studies that have not been included in this thesis.

Nopparat, N., B. Kianian, A.W. Thompson and T.C. Larsson. 2012. Resource Consumption in Additive Manufacturing with a PSS Approach. *4th CIRP International Conference on Industrial Product-Service System (IPS2).* The International Academy for Product Engineering (CIRP). Tokyo, Japan.

Hallstedt, S. and A.W. Thompson. 2011. Sustainability-driven product development – some challenges and opportunities for the aero industry. *International Society for Airbreathing Engines (ISABE) Conference.* Gothenburg, Sweden.

Ny, H., A.W. Thompson, P. Lindahl, G. Broman, O. Isaksson, R. Carlson, T. Larsson and K.-H. Robert. 2008. Introducing Strategic Decision Support Systems for Sustainable Product-Service Innovation across Value Chains. *Sustainable Innovation Conference.* Malmö, Sweden.

Ny, H., A.W. Thompson, K.-H. Robèrt, G. Broman, H. Haraldsson, D. Koca, and H. Sverdrup. 2009. Systems Modeling and Simulation within Sustainability Constraints: The Case of Waterjet Cutting. *Journal of Industrial Ecology.* (In review.)

Hallstedt, S. and A.W. Thompson. 2010. Integrating Sustainability and Innovation through a Master's Program in Product-Service Systems. *Knowledge Collaboration & Learning for Sustainable Innovation: 14th European Roundtable on Sustainable Consumption and Production (ERSCP).* Delft, The Netherlands.

Wallin, J., K. Chirumalla and A.W. Thompson. Designing PSS Scenarios Out of Traditional Sales Situation: The Use of Business Model Canvas. *5th CIRP International Conference on Industrial Product-Service System (IPS2).* The International Academy for Product Engineering (CIRP). Bochum, Germany. (Submitted).

Acronyms

B2B	Business to Business
B2C	Business to Consumer
BTH	Blekinge Institute of Technology (Blekinge Tekniska Högskola)
CAD	Computer Aided Design
C2C	Cradle to Cradle
CLD	Causal Loop Diagram
DfE	Design for Environment
DRM	Design Research Methodology
DSS	Decision Support Systems
EIA	Environmental Impact Assessment
EMS	Environmental Management System
FCA	Full Cost Accounting
FPD	Functional Product Development
FSSD	Framework for Strategic Sustainable Development
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LED	Light Emitting Diode
MSLS	Master's in Strategic Leadership towards Sustainability
MSPD	Method for Sustainable Product Development
MSPI	Master's in Sustainable Product-Service System Innovation
PSS	Product-Service System
REACH	Registration, Evaluation, Authorisation and restriction of CHemicals
RoHS	Restriction of use of Hazardous Substances
SBCE	Set Based Concurrent Engineering
SBD	Set Based Design
SCI	Sustainability Compliance Index
SDSS	Strategic Decision Support System
SLCA	Strategic Life Cycle Assessment
SLCM	Strategic Life Cycle Management
SMS	Systems Modeling and Simulation
SPI	Sustainable Product Innovation
SPSD	Sustainable Product-Service Development
SSD	Strategic Sustainable Development
TBL	Triple Bottom Line
TCA	Total Cost Accounting
TRL	Technology Readiness Level
TSPD	Templates for Sustainable Product Development
WEEE	Waste Electrical and Electronic Equipment

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Table of Contents

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1 Introduction

This chapter presents a background of the sustainability and product innovation issues that justify this research. Then the actual research gap that this research targets is identified (problem statement), followed by the aim and a reader's guide.

1.1 The Sustainability Challenge

Human society's awareness of our collective impact on the planet has been growing over the last several decades. Published in 1962, Silent Spring is credited with raising awareness of environmental impacts from the dangers of certain chemicals (Carson 1962; Downs 2004). The Limits to Growth study published in 1972 by the Club of Rome is often referenced as a significant awareness-raising study regarding the possibility of resource constraints for a rapidly expanding human population (Meadows et al. 1972).

In 1987, Our Common Future was published, providing this frequently cited statement about sustainable development:

> *Humanity has the ability to make development sustainable – to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs.*
> (World Commission 1987)

The World Commission's definition of sustainable development puts forth an attractive vision, but leaves a significant gap with regard to operationalizing this in practice. This has lead to many attempts to clarify the concept of sustainability (Pezzoli 1997; Johnston et al. 2007; Lozano 2008).

More recently, numerous publications have been put forth documenting impacts and opportunities, e.g. species loss (Millennium Ecosystem Assessment 2005), resource constraints (Gordon et al. 2006), anthropogenic climate change (IPCC 2007), and energy and material price responses to increased demand for these limited resources (Goklany 2009). "Planetary Boundaries" is an attempt to identify critical thresholds with regard to how society interacts with the ecological system (Rockström et al. 2009). At the same time, there are many social issues to be considered as the global context changes. Some of these issues are clearly related to environmental issues (e.g. access to potable water), while some are more purely social issues such as working conditions in supplier's factories or the issue of living wages.

Many ideas, concepts, methods, and tools have been developed to provide support in responding to the complex array of socio-ecological problems (e.g. Secchi 2007; ISO 2007; Cruz 2008; Dobers 2009; Lozano 2012). Throughout this work a specific concept designed to be unifying across sectors, disciplines and tools, methods and concepts, known as Strategic Sustainable Development (SSD) (Holmberg 1995; Broman et al. 2000; Holmberg and Robèrt 2000; Robèrt 2000; Robèrt et al. 2002;

Ny et al. 2006; Missimer et al. 2010) is used to help put perspectives and tools, methods and concepts in context of sustainability. This understanding of sustainability has been used to build tools and methods for sustainable product innovation before (e.g. Ny et al. 2006; Byggeth et al. 2007; Hallstedt 2008; Ny 2009). This is expanded upon in Chapter 3.

1.2 Sustainability in Product Innovation

Sustainability in the context of product innovation is important because designed artefacts and how people interact with them over the course of their life cycles are responsible for many of society's sustainability challenges (Kaebernick et al. 2003; Pujari 2006). It is generally possible for these to be considered and to some extent changed in the early stages of the product innovation process (Tingström et al. 2006; Johansson and Winroth 2010; Petala et al. 2010).

Simons et al. (2001) describe three generations of environmental strategies in product development. The first generation approaches were primarily focused on addressing environmental problems after they occurred. A more proactive second generation was underway by the mid-1980s, where environmental approaches were moving upstream in attempts to address pollution by preventing it in the production process, primarily by reducing point-source pollution at factories. In the early 1990s, a third generation appeared that focused on environmental impacts throughout the product life cycle. Product design has been suggested as an appropriate intervention point in a product's life cycle at which to implement environmental goals including sustainable waste management practices (Graedel and Allenby 1998; Giudice et al. 2006; Pongrácz 2009). Here ecodesign (e.g. Karlsson and Luttropp 2006) and design for environment (DfE) (e.g. Graedel and Allenby 1998) are well-known design methodologies, and life cycle assessment (LCA) (ISO 14040) is a well-known assessment methodology. However, they alone are not sufficient from a sustainability perspective due to e.g. considering only known environmental impacts or missing social aspects (Robèrt 2000; Ny et al. 2006), or not considering implications from potential "rebound effects" (Binswanger 2001).

The dominant mental paradigm in business today often puts (relatively short-term) financial profit forward as the primary goal. This paradigm is coming around to the need to more directly include both environmental and social issues in daily decisions (Porter and van der Linde 1995; Pujari et al. 2003; Dangelico and Pujari 2010). This is happening for many reasons: customer demand, expanding and more stringent regulations, global resource constraints, and perceived opportunities for cost savings to name just a few.

One reason product developers and engineers have left sustainability outside of their focus is that there is confusion generally around the concept of sustainability (Johnston et al. 2007; Lozano 2008), and more specifically the concept and how to address it within an engineering context (Glavic and Lukman 2007).

1.3 Product-Service Systems

While product development has traditionally focused on the development of tangible products, there is movement in industry towards the design of products and services together – often referred to as product-service systems (PSS) (Goedkoop et al. 1999; Mont 2002; Tukker and Tischner 2006). Since the end of the 1990s, the PSS research field has become well known in Europe and Japan. PSS are frequently represented on a continuum, with pure product on one side, pure service on the other side, and a product/service mix in the middle (explained more in Section 3.2). This movement, then, can come from manufacturers (i.e. "pure product") who add services, or from service providers who expand their offers by adding products.

PSS has been defined as a "*marketable set of products and services capable of jointly fulfilling a user's need*" (Goedkoop et al. 1999). It is also frequently referred to as a concept with potential to support incrementally or radically more sustainable solutions through reducing material and energy use due to a focus on the user's desired function (Roy 2000; Mont 2002; Manzini and Vezzoli 2003; Tukker 2004).

1.4 Problem Statement

The current state of practice in the area of sustainable product innovation does not sufficiently address the social and ecological challenges that society faces. Specifically, two problems are identified:

1. Common approaches to sustainability in product innovation are not sufficient to cover a robust systems perspective of social and ecological sustainability; and
2. A systems perspective would imply intimate cooperation between actors that together would represent the life cycles of products and services. However, evolution from "product development" to "PSS innovation" is very challenging.

1.5 Aim and Reader's Guide

This document intends as its primary audience people working in the area of product-service system innovation and those with an interest to bring strategic aspects of sustainability into the product innovation process. It attempts to provide inspiration and ideas to bridge the gap between product innovation that is common in practice today and product innovation that is informed, and even driven by, a strategic socio-ecological sustainability perspective.

There are different uses of "product" in different bodies of literature and in practice, i.e. "product" may take on the ISO definition to refer to "*the result of a process, i.e., a set of interrelated or interacting activities which transforms inputs into outputs, of which four generic categories are services, software, hardware and processed materials*" (ISO 2005). The term may also refer to a physical artefact, as it tends to do in product development literature. To the extent possible, the author uses "product" in line with the ISO definition, and uses the term "artefact" to refer to a physical, tangible object. Note, however, that this is not always possible due to the supporting literature.

To the extent possible, "design", "development" and "innovation" will be used in line with how Roozenburg and Eekels (1995) have described them: Product development comprises the development of the design of a new product in coherence with the plan for its production, distribution, and sales. Product innovation includes development and realization of the new product or process.

An introductory part and six appended papers make up this thesis. The introductory part has seven chapters with the contents outlined below.

Chapter 1: Introduces this work by focusing in from the broad background to the purpose of this research.

Chapter 2: Introduces the approach to research used in this thesis.

Chapter 3: Explores the knowledge domains related to this research by providing relevant information with related domains of sustainability and product-service systems innovation.

Chapter 4: Summarizes the appended papers regarding contents, relation to the thesis and how the work in those papers was divided between the authors.

Chapter 5: Presents a discussion of the research issues based on the papers that are included in this thesis.

Chapter 6: Summarizes this work's scientific and industrial contributions.

Chapter 7: Provides a concise conclusion of this work.

2 Research Approach

This chapter describes the author's approach to research, i.e. how this research topic has been approached and advanced.

2.1 Research Design

Research design deals with several aspects of research, including which questions to study, which data are relevant, what data to collect, and how to analyze results. Designing research is important because objectives, questions, and methods need to be aligned in order to arrive at reliable results. Furthermore, those methods and approaches should be considered, i.e. reflected upon and chosen with intention. A research methodology, then, should guide the selection and application of a suitable approach and appropriate methods. While the design of research may be updated or adapted as research progresses, the research planning process (research designing) is critical in order to be intentional about research – precisely why a research methodology is important.

Research designs can be categorized in three broad ways: exploratory, descriptive, or explanatory (Miles and Huberman 1994; Yin 2002).

- Exploratory designs are useful for obtaining basic knowledge on a topic, especially when the relations concerning the issue are new and unknown. Methods for research with an exploratory design usually include interviews, focus groups or case studies.
- Descriptive research designs are suitable for more clearly structured research problems. They aim to explain the characteristics of certain groups. These studies can further extend and develop basic knowledge that was generated during explorative research.
- Explanatory research designs can be used to study relations between cause and effect. This design aids in clarifying complex issues by determining how different factors interact.

These three broad categories of research are appropriate when studying "about" something, i.e. descriptive or explanatory, with that description or explanation making a contribution to the body of knowledge, and that contribution being the ultimate goal of the research. Action research, however, "aims to design inquiry and build knowledge for use in the service of action to solve practical problems" (Punch 2005, p 160). It is based on cycles of research and action to improve understanding, while gradually changing the system being investigated (Blessing and Chakrabarti 2009, p 273). This requires an additional prescriptive component in the research design. The Design Research Methodology (DRM) described below is, by design, of the action research variety. This research also intends to be of the action research variety, i.e. to not only describe and explain what is being studied, but also to enable using that understanding in practically relevant ways.

The initial design of this research began with a conceptual base in the approach to qualitative research design articulated by Maxwell (2005) and shown in Figure 1. As this thesis has gravitated towards the field of design research, it has been found helpful to adapt the Design Research Methodology (DRM) put forth by Blessing and Chakrabarti (2009) shown in Figure 2 and described below, which provides a more specific approach to research of this type. Following are brief descriptions of both.

2.1.1 Maxwell Qualitative Research Design

Maxwell's model provides a foundation for research in this thesis more generally and helps to provide a broader research framework for aspects of this research that have a broader perspective. The Design Research Methodology provides a methodology that hones in on specific aspects of design processes. Both perspectives are critical in order to ensure that what is in focus is important to take the time to study (Maxwell), and researched in an appropriate way for the focus area (DRM).

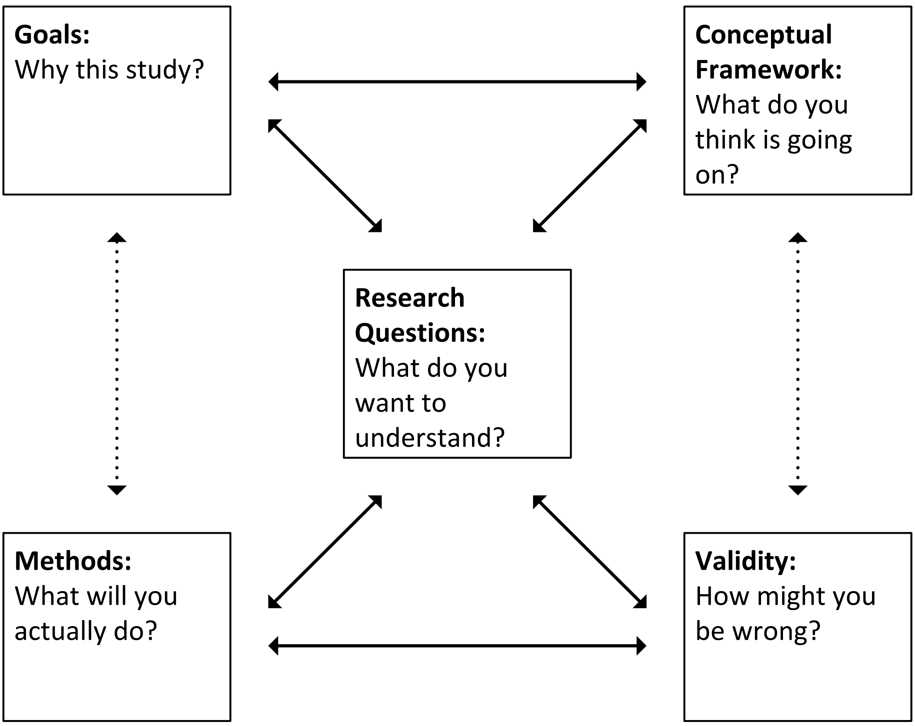

Figure 1: Maxwell's model for qualitative research design.

Maxwell suggests the following key aspects of research design:

Goals: Why is this study worth doing, what issues do I want to clarify, what practices / policies do I want to influence, why do I want to do this study, and why would anyone care about the results?

Conceptual Framework: What do I think is going on? What theories, beliefs, and prior research will guide/inform this research? How will I understand the people or issues I am studying?

Research Questions: What specifically do I want to understand by doing this study? What do I not know about the thing I am studying that I want to learn? What questions will my research answer, and how are these questions related?

Methods: What will I actually do in conducting this study?

Validity: How might my results and conclusions be wrong?

2.1.2 Design Research Methodology

The concept of Design Research was introduced by Blessing and Chakrabarti (2009) to address three related issues: lack of overview of existing research, lack of use of results in practice, and lack of scientific rigor. It was necessary to develop a specific approach for design research to address unique aspects in the design situation, e.g. the uniqueness of every design situation that is a result of creating a product that does not exist, having differences in the context in which a design project is happening, and the constantly changing or evolving knowledge and experience of team members. Furthermore, design research aims to both understand, as well as to influence, design – something that differentiates design research from more classical research methodologies.

2.1.3 Goals

The overarching goal of this research is to contribute to sustainable development of society by better understanding how strategic sustainable development aspects can be brought into and guide product-service system innovation. This work has largely been about understanding and some about providing support, as shown as "Main Outcomes" in Figure 2.

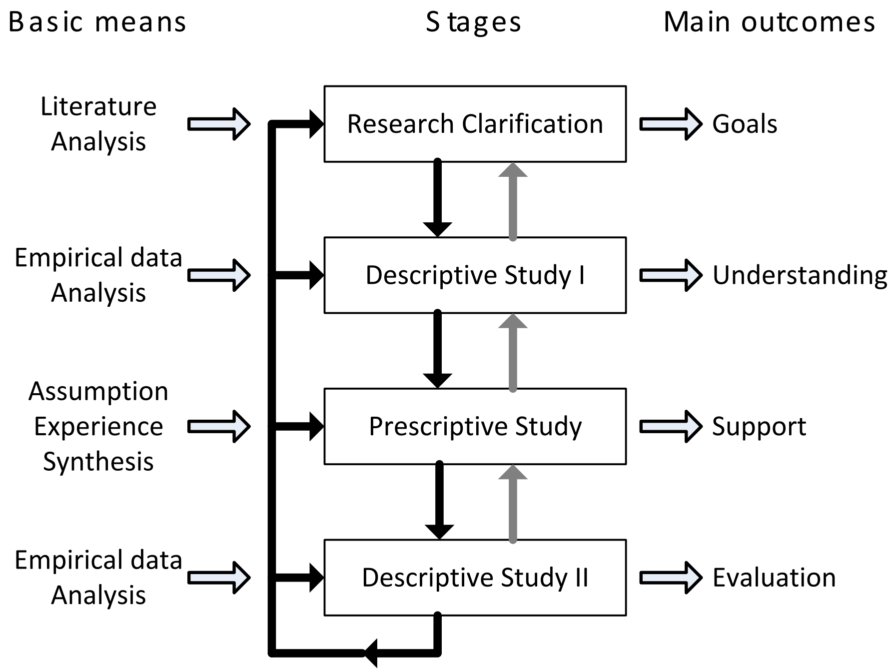

Figure 2: Design Research Methodology (DRM). Recreated from (Blessing and Chakrabarti 2009).

In order to build a foundation to reach those goals, this research sets out to assess the current state of practice of this integration and to clarify theoretical and practical possibilities and limitations for sustainability considerations to guide product-service system innovation. With that additional understanding, this work aims to contribute to the state of practice by exploring how to better support the development and implementation of product-service systems that are (i) (economically and otherwise) attractive to actors involved in the PSS while at the same time are (ii) supportive of global society moving towards socio-ecological sustainability. This work explores the intersection between sustainability and innovation, specifically with the opportunity for a product-service system (PSS) approach to be a critical vehicle for sustainability-driven innovation.

2.1.4 Research Questions

The collection of papers and articles included in this thesis each have their own specific research questions; these are summarized in Chapter 4. They all endeavor to contribute to answering the following overarching question:

- How can a strategic sustainable development (SSD) perspective be better integrated into product-service system innovation working environments in the manufacturing industry in a way that is mutually beneficial for the product-service system (PSS) provider(s) and society at large?

This implies a need to both consider:

- How can product-service systems (PSS) contribute to sustainable development of society?
- How can a strategic sustainable development (SSD) perspective contribute to product-service system innovation?

2.1.5 Scope and Limitations

The focus of this thesis is the interface where a strategic sustainable development (SSD) perspective (explained in section 3.1.1) meets product-service systems (PSS) (explained in section 3.2). This interface is explored in the context of the Swedish manufacturing industry with an emphasis on how the industry can pursue (more) sustainable products through product-service system innovation.

Even though there is significant work towards more environmentally-friendly products in related fields like life cycle assessment (LCA), ecodesign, and design-for-environment (DfE), thorough investigation of these concepts is outside the scope of this thesis. Furthermore, the strategic sustainable development perspective applied here is based on a previously published and continuously developing framework for strategic sustainable development; however, it is not within the scope of this thesis to further develop that framework.

At the same time, PSS-related research areas include e.g. mechanical engineering, service engineering and functional sales. All of these are disciplines that have much to offer in the way of designing and implementing PSS, but are also outside the scope of this thesis.

2.2 Methods

The following methods and techniques have been used, and are further elaborated upon within the papers that are included in this thesis.

2.2.1 Data Collection

- A broad survey of literature has provided an opportunity to explore the related topics and specifically focus on the intersection between these key topics, in order to better understand the past and present thinking within the research field. The results of this are presented primarily in Chapter 3, and also serve as a foundation through each of the appended papers.
- Interviews and interaction with people working within the area of product innovation were conducted in order to better understand and describe the state of practice in industry. These provide general background support for ideas and arguments presented in Chapter 4 and paper A, and they are central to the research presented in papers B, C, and D.
- Participation in and facilitation of workshops with development teams with companies involved in the research project that were intended to aid

companies in including sustainability in their thinking around product innovation, specifically using methods/tools previously developed by BTH. These workshops were conducted with Dynapac, Roxtec, Aura Light International AB, SAPA Heat Transfer, Tetra Pak, Volvo Aero Corporation (now GKN Aerospace Engine Systems), and Volvo Construction Equipment.

These methods are in line with the first three stages of the design research methodology (DRM) as illustrated in Figure 2.

2.2.2 Qualitative Data Analysis

Miles and Huberman (1994) provide a framework for qualitative data analysis that has informed this research. This framework has three main components: data reduction, data display, and drawing and verifying conclusions. For data reduction, they note that it is especially important not to remove qualitative data from its context, i.e. that context is important to the data collected. Punch (2005), summarizing this framework, notes that good qualitative research involves repeated and iterative displays of data. Conclusions are drawn both during data display and data reduction, and after being drawn should be verified.

2.2.3 Understanding through Teaching

The opportunity to make significant contributions in planning and delivering the curriculum and pedagogy for two master's programs ("Strategic Leadership towards Sustainability" (MSLS) and "Sustainable Product-Service System Innovation" (MSPI)) has been instrumental for the author's own development.

2.3 Validity

Demonstrating the validity of design research is challenging for the reasons described earlier. Transcripts provide the words that comprise an interview, and meeting notes and workshop summaries capture the essence of discussions and workshop activities. However, these do not reflect the essence of the research that happens where the researcher's unique worldview and experiences come to bear on the words that are shared in the time and context in which they are spoken. Certainly these can never be repeated as a controlled experiment, for all – the researcher, the interviewee, and the context – will have changed. And yet, something can be – is – learned in the process.

For research to have the potential to be good, several things need to happen:

- A researcher needs to have self awareness sufficient to realize how (s)he influences the research process, including how his/her own frameworks and mental models form the lens through which (s)he views the problem being explored. It helps to make these as explicit as possible.
- When doing research, trust those frameworks and mental models such that (s)he can sufficiently engage in the research process in order to focus on the

problem/question at hand and not continuously question the basis of the framework being relied upon.

- Upon completing research methods, return to the questioning of frameworks and mental models, e.g. to see if there are ways for them to be updated, to consider how those aspects of improvement may have influenced the validity, etc.

2.4 Values, Sustainability, and Science

Sustainability requires trans-disciplinary research that is founded on the idea that "*society is facing problems manifest in the real world that are complex, multidimensional, and not confined by the boundaries of a single disciplinary framework*" (Wickson et al. 2006). Max-Neef (2005) writes that trans-disciplinary research is the result of coordination between four levels. The first is the empirical level, and asks the question "*what exists?*" Things like physics, biology, and economics help to provide answers. The next (pragmatic) level asks "*what are we capable of doing?*" Through technical disciplines, we know how to build e.g. airplanes, travel in space, and build nuclear energy facilities. The next (normative) level asks the question "*what is it we want to do?*" Answers are provided through e.g. laws and planning. The fourth (value) level asks "*what should we do?*" or "*how should we do what we want to do?*" and goes beyond the present and the immediate (Max-Neef 2005). Max-Neef then suggests that it may be time for us as humans to go beyond knowing so that we might improve understanding:

> *If I were asked to define our times, in few words, I would say that we have reached [a] point in our evolution as human beings, in which we know very much, but understand very little. It goes without saying (evidences are clear) that linear logic and reductionism have contributed to our reaching unsuspected levels of knowledge. The knowing has grown exponentially, but only now we begin to suspect that that may not be sufficient, not for quantitative reasons, but for qualitative reasons. Knowledge is only one of the roads, only one side of the coin. The other road, the other side of the coin, is that of understanding.*
> (Max-Neef 2005)

The points that Max-Neef brings forward here are particularly relevant in sustainability-related research. Briefly, an example of why this may be true: it is easy to reduce sustainability considerations in product innovation to the level of trying to quantify known environmental impacts of products across their life cycles. Of course knowledge of these impacts can be useful in order to make decisions. However, as we go along the sustainability journey, it is about far more than understanding these known impacts, and it becomes much more about the questions asked at these higher levels: "*what do we want to do?*" and "*what should we do?*" Max-Neef is giving us permission to embrace these questions – often and traditionally placed beyond the bounds of "science" – as part of the scientific dialogue.

This thesis does not attempt a dive into these value-based discussions. Rather, it attempts to remain rooted in the also nascent area of design research, for there is a strong desire by the author to remain grounded in order to have a concrete effect on development processes. However, it is critical from a research design perspective to acknowledge that these values underlie much research work in the sustainability field.

3 State of the Art

This thesis draws upon two broad areas: (1) sustainability, and specifically the concept of strategic sustainable development, and (2) product-service system innovation, especially from the manufacturing perspective. Sustainability helps set the direction, e.g. becoming "more sustainable" or working towards a sustainable society.

3.1 Sustainability

There is a great deal of research work relating to sustainability happening in the world today, and there are many approaches to defining and working with sustainability and sustainable development in general (Hopwood et al. 2005; Johnston et al. 2007; Lozano 2008), and product innovation specifically (e.g. Baumann et al. 2002; Glavic and Lukman 2007).

There remains much discussion on how to think about sustainability broadly. One example: is "weak" versus "strong" sustainability. A "weak" sustainability approach assumes the possibility for either unlimited substitution among different kinds of capital (e.g. economic, social, environmental) or that money can be substituted for anything (e.g. Gowdy 2005). A "strong" sustainability approach suggests that these types of capital complement each other, but cannot be substituted (e.g. Daly 1990). The precautionary principle is another key point of debate in the sustainability community with complicated and value-based implications for decision-making (e.g. Manson 2002; van den Belt 2003; Cooney 2004), especially but not limited to the area of biotechnology (van den Belt 2003). The time perspective is also a frequent consideration, as indicated in the World Commission's definition with reference to "present" and "future" generations (World Commission 1987; Lozano 2008).

Within the business management community, sustainability is sometimes considered from economic, environmental and social perspectives, known as the "triple bottom line (TBL)" (Elkington 1998). The TBL concept is not universally supported; it has e.g. been referred to as "*good old-fashioned single bottom line plus vague commitments to social and environmental concerns*" (Norman and MacDonald 2004).

Given the range of perspectives, opinions, and approaches to addressing sustainability in the world, it is not possible to review them all here (e.g. Johnston et al. 2007; Lozano 2008). As described in the scope (2.1.5), with regard to sustainability, this thesis work builds upon the foundation that has been put forth in recent decades of a framework for strategic sustainable development (FSSD). This FSSD aims to provide i) clarification of what is to be sustained, ii) an operational definition of sustainability, and iii) an initial set of strategic guidelines that can be used to provide guidance to decision-makers, including decision-makers who work with product innovation.

3.1.1 Framework for Strategic Sustainable Development

A framework for strategic sustainable development (FSSD) can be helpful to clarify the concept of sustainability and to provide guidance towards a sustainable human society. It consists of the following elements.

Five-Level Structure

A five-level structure (Figure 3) provides five clearly distinct (but interacting) levels, suggesting that it is imperative to first agree upon the system (level 1) that is to be planned within, and only then to go on to define success (level 2) within that system. After defining success, then strategic guidelines (level 3) can be determined for the selection and prioritization of actions (level 4); all four of these levels can be supported with various concepts, methods, and tools (level 5) (Robèrt 2000; Robèrt et al. 2002). Levels 2-3 also provide support for the further study of the system (level 1), i.e. identification of the relevant and essential aspects of the system that need to be further studied with regard to reaching the defined success. It is the rigor by which levels 1-3 are described and allowed to inform each other that determines how confident users can be when developing/choosing appropriate actions (level 4) and appropriate complementary concepts, methods and tools (level 5).

Level	**Framework for Strategic Sustainable Development (FSSD)**
(1) System	Society (within the ecosphere)
(2) Success	Sustainability principles
(3) Strategic Guidelines	Guidelines to select and prioritize actions, e.g. backcasting
(4) Actions	Concrete actions that follow the strategic guidelines
(5) Tools	Concepts, methods and tools that support the process

Figure 3: Framework for Strategic Sustainable Development.

Unique Definition of Success: Sustainability Principles

By first agreeing upon the system to be sustained (i.e. the global social and ecological systems), one can then go on to ask the question: "*Which mechanisms can cause systematic destruction of this system?*" If that question is answered in a way such that the results are statements that are general, concrete, sufficient, necessary, and non-overlapping, one then arrives at what are, in essence, boundary conditions for a sustainable society. One set of statements that strives to answer this question in this way is the FSSD's "Sustainability Principles". These state that in a sustainable society, nature is not subject to systematically increasing (Ny et al. 2006):

1. Concentrations of substances extracted from the Earth's crust;
2. Concentrations of substances produced by society;
3. Degradation by physical means;

And, in that society…

4. People are not subject to conditions that systematically undermine their capacity to meet their needs.

The fourth principle in particular is in need of further development (Upham 2000; Sandström 2005) and that development is in progress (Missimer et al. 2010).

Backcasting

Changing the perspective of time from one that exists primarily in the present with one eye towards the past to a perspective that is focused equally on the present and the desired future, with a cognizance of the past, could help society to disconnect from past trends in order to e.g. get to a level of carbon in the atmosphere that is "safe". Such an approach is known as backcasting, where one puts oneself in a desired future and looks back to the present, asking the question: "*How did we get where we wanted to go?*" (Robinson 1990; Dreborg 1996; Holmberg and Robèrt 2000).

Quist et al. (2011), based on a literature review and three case studies, find that participatory backcasting experiments can provide orientation – "where to go" – and guidance – "what to do" – for involved stakeholders, and as such is a promising alternative to traditional planning. They caution, however, that backcasting exercises do not necessarily lead to direct action, which is largely dependent upon both internal and external factors that can either constrain or support the likelihood of action occurring.

Why the FSSD?

When backcasting is combined with the unique definition of success (based on boundary conditions for a sustainable society as described in the previous section, as opposed to backcasting from the implementation of specific scenarios), the result is "backcasting from success within sustainability principles" that allows for strategic decision-making that ensures flexibility, movement towards a sustainable future, and (more) appropriate allocation of resources (Holmberg and Robèrt 2000).

The FSSD, while still developing (Missimer et al. 2010) and not without critics (e.g. Upham 2000; Sandström 2005; Lozano 2012), provides an approach to sustainability that is "*helpful in preventing problem displacement and in designing future problems out of the system*" (Baumgartner and Korhonen 2010). A number of previous studies have shown that the FSSD is effective for strategic step-by-step decision-making in companies (Robèrt 1994; Nattrass 1999; Broman et al. 2000; Everard et al. 2000), for sharing of mental models in community-building (Nattrass 1999;

Nattrass and Altomare 2002), for the assessment of various kinds of tools and concepts for sustainable development in general (Robèrt et al. 2002; Robèrt et al. 2013) including ecodesign tools (Byggeth and Hochschorner 2006) and for company decision systems (Hallstedt et al. 2010). It thus supports a more sophisticated view on sustainability that was identified as a problem in section 1.4.

Furthermore, the FSSD is unique in that it combines the backcasting approach together with a definition of sustainability based on first-order principles that strive to be necessary, sufficient, general, concrete and non-overlapping (Missimer et al. 2010) rather than only attempting to minimize known, negative impacts (which may not be sufficient to reach societal sustainability) or pursuing a utopian ideal (which is not necessary to achieve sustainability) (Johnston et al. 2007).

3.2 Product-Service System Innovation

The concept of product-service systems (PSS) emphasizes a shift in the focus from selling only a tangible artifact or intangible service to selling the result of a combination of products and services. Definitions of PSS typically include reference to increased competitiveness of PSS providers and possibly to increased revenue opportunities. Some definitions do not explicitly include reference to reduced environmental impacts (e.g. Manzini and Vezzoli 2003; Wong 2004). However, many PSS definitions do include reference to reduced negative environmental impacts (e.g. Goedkoop et al. 1999; Mont 2004; Wong 2004; Baines et al. 2007). This potential for improved environmental performance, together with the increased revenue potential, makes PSS an attractive area of focus for this thesis.

The field of PSS design is currently at only an initial stage of development (Mont 2002); potential financial and environmental benefits have been identified, but the field requires substantial research in order to enable a transition from traditional product development (Pawar et al. 2009) and to mature as a field (Vijaykumar et al. 2012).

3.2.1 Innovation

Innovation, generally, refers to new products, processes or ideas that are put into use. "Innovation" differs from "invention" which is the first occurrence of the idea of those new products or processes, in that innovation implies inventions that are put into practice. Schumpeter lists five types of innovation: new products, new methods of production, new sources of supply, exploitation of new markets, and new ways to organize business (Fagerberg et al. 2006). Much of the research reported in literature is focused on better understanding the first two in that list, which are commonly referred to as "product innovation" and "process innovation".

Innovation literature frequently comes from the social sciences with roots originating with e.g. Schumpeter. Innovation references also originate from within the field of engineering e.g. Roozenburg and Eekels (1995) or Ulrich and Eppinger (2008). One related observation is presented by Kline and Rosenberg:

> *Economists have, by and large, analyzed technological innovation as a "black box" – a system containing unknown components and processes. They have attempted to identify and measure the main inputs that enter that black box, and they have, with much greater difficulty, attempted to identify and measure the output emanating from that box. However, they have devoted very little attention to what actually goes on inside the box; they have largely neglected the highly complex process through which certain inputs are transformed into certain outputs.*
>
> *Technologists, on the other hand, have been largely preoccupied with the technical processes that occur inside that box. They have too often neglected, or even ignored, both the market forces with which the product must operate and the institutional effects required to create the requisite adjustments to innovation.*
> (Kline and Rosenberg 1986):

It is often challenging to arrive at a shared vocabulary between these different perspectives. Throughout this work, literature is drawn from both social science and engineering perspectives.

Types of Innovations

Innovation is a broad topic, and as such, many attempts have been made to divide or to categorize aspects of innovation. This section introduces a few of the key categories of innovation that may be referred to throughout this dissertation.

One approach to classifying innovations with roots in Schumpeter's work relate to how radical an innovation is relative to the status quo. Continuous improvements are considered to be "incremental" innovations; these are in contrast to "radical" innovations that result in more significant changes. Implications for organizational structure and firm strategy have been considered for decades (e.g. Ettlie et al. 1984) and have continued to be explored more recently (e.g. Valle and Váquez-Bustelo 2009).

"Product innovation" and "process innovation" are used to "*characterize the occurrence of new or improved goods and services, and improvements in the ways to produce these goods and services, respectively*" (Fagerberg et al. 2006, p. 7). Schumpeter defined 'product innovation' as "*the introduction of a new good… or a new quality of good*" and 'process innovation' as "*the introduction of a new method of production… or a new way of handling a commodity commercially*" (Schumpeter 1934, as cited in Fagerberg et al. 2006, p. 572). Caroli and Van Reenen state:

> *The distinction between product and process innovations should not be carried too far. Most innovative firms introduce both at the same time, but in most firms and industries it is possible to identify the dominant orientation of innovative efforts, associated with strategies of either price competitiveness (and mainly process innovations) or technological competitiveness (and mainly product innovations). In*

> *addition to product and process innovations, organizational innovation also can affect the quantity and quality of employment, and is usually closely linked to the introduction of new technologies.*
> *(*Caroli and Van Reenen 2001, as cited in Fagerberg et al. 2006, p. 573)

As summarized by (Damanpour and Gopalakrishnan 2001):

- "Product" is a good or service offered to the customer or client;
- "Process" is the mode of production and delivery of the good or service (referring to Barras 1986);
- "Product innovation" is new products or services introduced to meet an external user or market need;
- "Process innovation" is new elements introduced into an organization's production or service operations (e.g. input materials, task specifications, work and information flow mechanisms, equipment) to produce a product or render a service (Knight 1967; Utterback and Abernathy 1975; Ettlie and Reza 1992).

3.2.2 Product Development / Innovation Processes

In order to be able to develop tools and methods to integrate into existing product innovation working environments, it is important to have a base understanding of how the product innovation process is perceived. Many models of the product development and/or product innovation process exist. When considering possible interventions for including sustainability aspects in product innovation, it is helpful to consider these different models and their varying levels of complexity. Originating from a western manufacturing perspective, the Roozenburg and Eekels (1995) model is used in Papers A and B to provide clarity with what is meant with some key terms; they provide a distinction between product development and product innovation, suggesting that product innovation is a process that includes product development together with realization. Other authors use different descriptions of the process. For example, Ulrich and Eppinger (2008) define product development (PD) as "the set of activities beginning with the perception of a market opportunity and ending in the production, sale and delivery of a product". This definition for "product development" more closely matches with what Roozenburg and Eekels refer to as "product innovation".

3.2.3 Set-Based Product Development

Set-based design (SBD) is often described in contrast to point-based design; each describing a different way of reaching a final design concept. Singer et al. (2009), referring to Liker et al. (1996), list five basic steps for point-based design strategies:

1. The problem is defined.
2. A large number of alternative design concepts are generated.

3. Preliminary analyses are conducted and a single concept is chosen for further development.
4. The selected concept is modified until all of the product's requirements are met.
5. If the selected concept fails to meet requirements, the process restarts at step 1 or 2.

In contrast, the main features (not steps) of set-based design are as follows (Singer et al. 2009), and is illustrated in Figure 4:

- Broad sets of design parameters are defined to allow concurrent design to begin.
- Sets are kept open longer than in point-based design in order to more fully define trade-off information.
- Sets are gradually narrowed until a more globally optimum solution is found.
- As sets are narrowed, the level of detail of the design increases.

The SBD approach has many similarities with the Method of Controlled Convergence (MCC) supported by Pugh (1991) and the design-test-build cycle supported by Wheelwright and Clark (1992); see (Bernstein 1998) for a discussion of similarities and differences.

Ward et al. (1995) write that several aspects of concurrent engineering (CE) are evident in the approaches of Toyota (together with its suppliers), and that none of the concepts are new. They strongly advocate, however, that the set-based philosophy of Toyota was a key factor of its success, and they list several reasons why. One to emphasize here: the "ambiguity" that seemed to be inherent in Toyota's communication to its suppliers – due to describing the boundary conditions for a solution space rather than precisely describing a specific concept – is actually great precision because Toyota would only communicate the constraints of the solution space for which it was confident. Sobek and Ward (1996) say it this way: "*Organizations that do not communicate sets and look for their intersections wind up trying to marry independently optimized components. Toyota, on the other hand, looks for solutions that optimize total system performance.*" Thus solution space would never be expanded, but only continuously constrained (Ward et al. 1995).

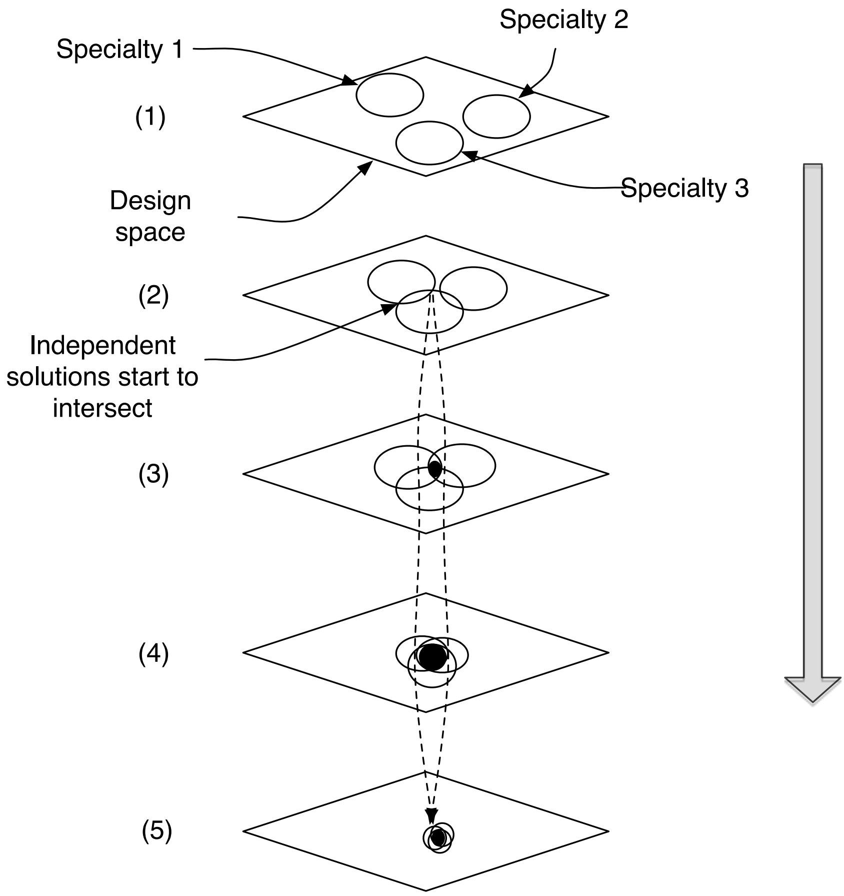

Figure 4: (1) Three specialties are illustrated within the design space (which contains all possible solutions). (2) The specialties expand the number of options they consider to establish a region of overlap between their design solutions. (3) The specialties work together to expand the region of overlap, increasing the number of solutions that satisfy all requirements. (4) Specialties then begin to eliminate options, so that the region of overlap shrinks. (5) The solution space is narrowed until only one solution remains. Recreated from Bernstein (1998), with credit to William Finch.

3.2.4 Life Cycle Perspectives

There are at least two primary ways to consider the product "life cycle". Cao and Folan (2012) provide a review of these two concepts with a shared name. Briefly, the first is the economic life cycle of a product, frequently seen in marketing literature, showing how development costs are incurred early, and then revenue begins to exceed costs in later stages. Stages typically include "introduction", "growth", "maturity", "saturation", and "decline". The length of time in each stage can vary by industry, customer base, the pace of technology development, and other factors. According to Cao and Folan (2012), this way of thinking about product "life cycles" dates back to the 1950's. Some authors have suggested that the concept is not valid (e.g. Dhalla and Yuspeh 1976; Wood 1990) and yet it continues to be relatively common in literature (e.g. Aitken et al. 2003).

The second type of product life cycle is based on what Cao and Folan (2012) call the "engineering product life cycle", originating from life cycle costing (LCC) and life cycle assessment (LCA). Life cycle stages here typically follow the material flow, i.e. raw materials, production, transportation/distribution, use, and end-of-life. Throughout the remainder of this thesis, "product life cycle" will refer to this type.

In addition to product life cycles, Tan et al. (2006) describe a "customer relationship life cycle" that intersects with the product's life cycle during the product's use phase to acknowledge that in addition to the life cycle of the artefact, there are additional perspectives to be considered, e.g. the customer's journey with regard to the product.

3.2.5 Servitization

Vandermerwe and Rada (1988) defined the term "servitization" as the offer of integrated packages of products, services, support, self-service and knowledge to add value to the company's core business. In developed countries especially, companies have struggled to survive purely as manufacturing enterprises (Karlsson 2007) and the role of the traditional manufacturing companies has become less attractive (Wise and Baumgartner 1999). This has required a shift in mentality from being a "good producer" to a "solutions provider" and includes a shift from mass consumption to a focus on individual behavior and personalized needs (Morelli 2002).

Services Add Value to Customers

Studies have given strong indications that services can create value for society and customers by increasing longevity and performance of the product (Mont 2004; Kim et al. 2007). However, some studies have demonstrated doubt about the ability of manufacturing companies to capture value when engaging in service activities (Oliva and Kallenberg 2003; Gebauer et al. 2005; Neely 2008). Visnjic and Van Looy (2011) suggest that companies need an integrated service business model in order to benefit from a servitization strategy and transcend the "service paradox" presented by Gebauer et al. (2005). Mathieu (2001) hints at the same point by concluding the most ambitious service strategies are the ones that provide manufacturing companies with the greatest benefits, but they are also the riskiest because of costs associated with implementation. Neely et al. (2011) conclude that it is likely more a question of execution of a servitization strategy (how well the company builds the right organizational capabilities and culture), rather than the act of servitizing, that leads to improved financial performance.

Neely (2012) provides three broad reasons why servitization is currently gaining in importance:

1. The changing structure of the global economy;
2. The technological dimension, where new advances open opportunities for service business model innovation; and
3. The future, with its anticipated stresses and strains coming from an aging population and changing societal expectations.

Services as Knowledge-Enhancing Opportunities

Doultsinou et al. (2009) explore how service knowledge can be (re-)used in design processes to enhance the design of products. They conclude that there are three main areas in which service knowledge can enhance design; these are improved:

1. In-service reporting, including operating conditions and failure records;
2. Access to operation environment descriptions: installation environment, tooling availability, accessibility, floor space, type and location of utilities, temperature and humidity and delivery route topology; and
3. Access to service facility descriptions: equipment type and dimensions, tooling availability and service process methods.

Here the emphasis is on how the proximity of customer support staff and customers in their operating environments contributes to knowledge of product improvement opportunities. Similar to the point made by Neely et al. (2008) regarding the right organizational capabilities, Doultsinou et al. (2009) observe: "there is not an adequate mechanism of interaction and feedback between new product development and service groups in place".

Services and Materialization

Roy (2000) points out how for the past 40-50 years, many services have "materialized" (become more dependent upon materials) as they have moved from centralized facilities into people's homes. The example he uses is clothes washing; with the introduction of the washing machine to the house, many of these machines were produced.

Challenges of Servitization

Much has been written on the challenges of moving towards PSS for manufacturing firms, with a heavy emphasis on the challenges of moving into services. Ritzén and Ölundh (2002) found in a study of Swedish companies providing product-service offerings three types of challenges:

1. Economic challenges, e.g. risks and internalization of costs for service and maintenance;
2. Internal challenges, e.g. need for changes in the company culture; and
3. Customer-related challenges, e.g. need for new relationships with the customers.

Alonso-Rasgado et al. (2004) report on insights into expectations on the changed business model that servitization or "functional (total care) products" entail. Brax (2005) identifies six challenges for a manufacturer becoming a service provider that relate to:

1. Marketing, e.g. motivating customers to the co-production that services require;
2. Production, both an integrative information system and good information management practices are fundamental to providing complex industrial services;
3. Delivery, e.g. services require a change in thinking throughout the providing company;
4. Product design, e.g. services may need to be adapted to fit customer cultures and fit customer goals;
5. Communication, which is needed to support the co-production that services depend upon, and must be presented as care instead of opportunism; and
6. Relationship, e.g. "the implicit transaction-oriented business philosophy of the manufacturer does not support service offerings", so services cannot simply be added on top of goods-dominant logic, rather a more radical approach is required.

Pawar et al. (2009) write about the "PSO [product-service-organization] Triangle" and suggest that the organization aspect, together with a focus on product and service, is critical because value can be most effectively delivered by networks of collaborating firms. Isaksson et al. (2009) emphasize similar challenges in developing PSS, e.g. how product development is organized, collaboration between service developers and traditional product developers, and ways of including the voice of the customer throughout the product development process. Martinez et al. (2010) identify five categories of challenges for organizations trying to move from product oriented to product-service oriented organizations:

1. Embedded product-service culture;
2. Delivery of integrated offerings;
3. Internal processes and capabilities;
4. Strategic alignment; and
5. Supplier relationships.

Furthermore, the economics of servitization are debated (Neely et al. 2008; Neely 2012). For example, Visnjic and Van Looy (2009) argue that there is compelling evidence of the [economic] benefits, often based on in-depth studies of a specific firm. Fang et al. (2008) suggest that firms will fail to reap the benefits from servitization until the firms reach a certain (minimum) level of service revenue. Gebauer et al. (2005) identify a "servitization paradox" in which firms invest in servitization, but do not see the expected returns on those investments. They point out that servitization has both a behavioral and an organizational dimension, and that managers are often unprepared for the complexity of it, preventing those expected returns from actually happening.

3.2.6 Categorizing PSS

There are multiple ways of categorizing PSS. This section presents three of them.

Basis of Sales on a Product/Service Continuum

Three categories of PSS have appeared in literature as early as 1993 (Mont 2000, citing Hockerts et al. 1993): product-oriented, use-oriented, and result-oriented. These types are differentiated based upon what is paid for by the customer; in product-oriented PSS the product (artefact) is sold. In the use-oriented PSS, use of the product is the basis of payment. In result-oriented PSS, the functional result is the basis of payment. Tukker (2004) presents eight types of PSS, which he divides into these three categories and presents on a product–service continuum as shown in Figure 5.

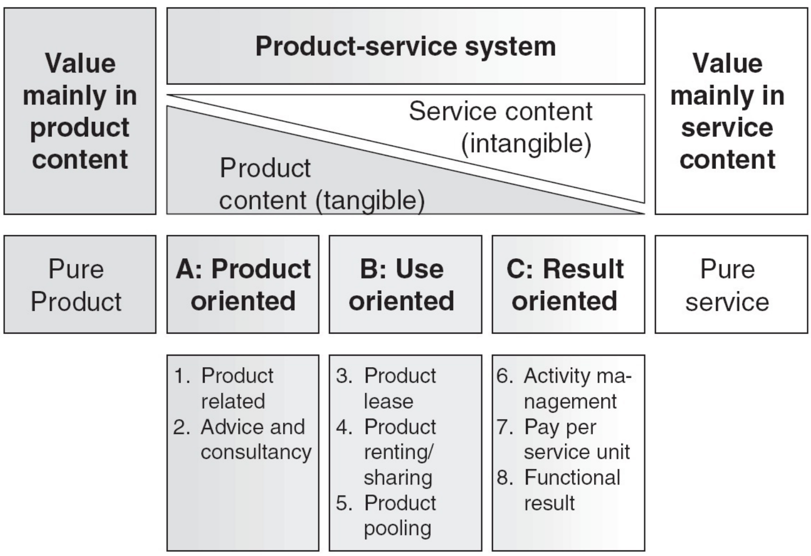

Figure 5: Eight types of PSS, including main categories of PSS. Recreated from (Tukker 2004).

Servitization Opportunities

Based on the extensive empirical data on 10,028 firms from 25 different countries, Neely (2008) describes twelve different forms of service (1-design and development, 2-systems and solutions, 3-retail and distribution, 4-maintenance and support, 5-installation and implementation, 6-financial, 7-property and real estate, 8-consulting, 9-outsourcing and operating, 10-procurement, 11-leasing, and 12-transportation and trucking). Neely (2008) then adds two new categories—integration-oriented PSS and service-oriented PSS—to the Tukker (2004) classification. Integration-oriented PSS result when firms seek to add services by going up- or down-stream and vertically integrating (e.g. consulting services, financial services, retail and distribution, transportation and trucking services and property and real estate services) whereas service-oriented PSS result when firms incorporate services into the product itself (e.g. systems and solutions).

Ownership Aspects

Clayton et al. (2012) take Neely's five types, and consider them from an ownership perspective as described in Table 1.

Table 1: Definitions of PSS Types Based on Ownership (recreated from Clayton et al. 2012).

Type of PSS	Definition
Integration-oriented	Adding services through vertical integration. Ownership is transferred to the customer, but the supplier seeks vertical integration (e.g. by adding retail, transportation services, etc.) (Neely 2008)
Product-oriented PSS	Ownership of the tangible product is transferred to the customer, while included in the original act of sale are additional services (e.g. maintenance, repair, re-use, recycling, training, consulting, etc.) (Baines et al. 2007)
Service-oriented PSS	Incorporate services into the product itself. Ownership of the tangible product is transferred to the customer, but additional value-added services are offered as an integral part of the offering (e.g. health usage monitoring systems) (Neely 2008)
Use-oriented PSS	Ownership of the tangible product is often retained by the service provider. Functions of the product are sold via modified distribution and payment systems (e.g. through sharing, leasing, etc.) (Neely 2008)
Result-oriented PSS	Selling the result or capability instead of a product (e.g. web information replacing directories). Companies offer a customized mix of services where the producer maintains ownership of the product and the customer pays only for the provision of agreed results (Baines et al. 2007)

3.3 Sustainability Aspects in Product Development

Much has been written over the past few decades about including some aspects of sustainability in the product development process, especially environmental issues. Van Weenen (1995) reviews some key concepts such as "pollution prevention," "Design for Environment (DfE)," and "Green Chemistry." Baumann et al. (2002) review the "green product development field" by looking at tools, processes in a company context, processes in a product chain perspective, and policy that is relevant to the topic. Maxwell and van der Vorst (2003) elaborate on the concept of "Sustainable Product and Service Development (SPSD)" as a further step, indicating that it builds upon "Eco-Design" which built upon "Design for X" methods. SPSD is focused on fulfilling traditional product criteria and sustainability requirements, and include an openness to PSS and emphasis on product functionality. Byggeth et al. (2007) brings in a framework for strategic sustainable development (FSSD) as a way to clarify the concept of sustainability, and integrates this framework with a generic product development process to arrive at a "Method for Sustainable Product Development (MSPD)."

3.3.1 Related Tools, Methods, and Concepts

Baumann et al. (2002) identified over 650 articles published from 1970-1999 presenting more than 150 tools and methods to integrate ecodesign into product development. They propose a framework that includes four levels:

1. The product development process and tools as such;
2. The product development process in a company context, i.e. relating to business strategy, management, marketing, etc.;
3. The product development process in a product chain perspective; and
4. Product development in relation to policy-making.

They also identify several "white spots" on the map of research on environmental product development, such as:

- An understanding of the use and role of tools on a micro level (within companies);
- An understanding of how this micro-level interacts with the macro level (between companies and in public policies); and
- Strategic orientation on the product development process within companies is underdeveloped.

And they conclude that "*researchers...need to adopt a more systemic perspective [because] the internal process of product development is related to other processes...*" (Baumann et al. 2002).

Bovea and Perez-Belis (2012) conducted a similar study where they elaborate a complex taxonomy for reviewing ecodesign tool integration into the product design process. They cite Knight and Jenkins (2009) to support their conclusion that techniques have not been widely adopted by businesses because they are not generic and immediately applicable to product development working environments. Bovea and Perez-Belis further conclude that:

> *...despite the wide variety of tools developed for integrating the environmental aspect into the design process, its implementation is scarce and the case studies are, in many cases, theoretical examples, without the backing of a product design company…[m]ost of [the ecodesign tools] are not applied in a systematic way in companies due to their complexity, the time required to apply them and the lack of environmental knowledge. That is why these support tools ... should be easy to use and not require too much time to be applied.*
> *(*Bovea and Perez-Belis 2012)

Bovea and Perez-Belis (2012) then elaborate three key factors that should make up an ecodesign tool as follows:

1. Early integration of environmental aspects into the product design and development process;
2. The life cycle approach, which takes into account how the product can affect the environment in its different stages; and
3. A multi-criteria approach.

Then they suggest that even though there are such tools in existence, "their implementation depends on the interests of the company," suggesting that even if very good ecodesign tools already exist, there are other factors that determine if those tools get used (Bovea and Perez-Belis 2012). This leads back to the work of Knight and Jenkins (2009), who conclude:

- Strategy tools would usually be over-ruled by customer specifications, implying a lack of freedom in applying ecodesign and restricting the company's scope to implement a self-determined strategy. So the process should work within these limitations and omit such tools, at least until an 'ecodesign culture' is well established;
- Some tools are more appropriate than others (e.g. longevity could take priority over disassembly and recycling). So the procedure needs to adopt only process-compatible tools that show clear benefits and include only those for which staff are prepared to take responsibility;
- Some tools represent common sense (e.g. the "10 Golden Rules" – "we do it anyway"), but lack specificity. So where they are already inherent in the design process they need recognition and development;
- Ease of use, complexity, and resource impact (i.e. staff time) is common themes, and to some extent, these factors are inter-dependent. The need for staff training and development has been identified and should ease concerns in these areas;

- Other pressures come to bear during the product development process. This may be the greatest obstacle, as time is always a limited design resource.

Beskow and Ritzén (2000) note that industry commonly sees the implementation of the support tools that address environmental issues as a way of increasing their efficiency during the product development process. Motivating factors for industry to adopt ecodesign has been studied by many authors (e.g. Boks 2006; Le Pochat et al. 2007). Luttrop and Lagerstedt (2006) argue that environmental aspects are not in design requirements and therefore not given attention, and that benefits to customers must be "balanced" with corresponding environmental impacts. Knight and Jenkins (2009) suggest that they are not widely implemented due to not being generic and immediately applicable to varying design contexts, in essence suggesting that if it were easy, it would be done. Others who view sustainability aspects simply as additional design requirements assume that addressing additional requirements will both further limit design space and add costs to product development. Plouffe et al. (2011) conclude that ecodesigned products have clear short-term benefits through higher revenues and volumes of sales while frequently having lower variable costs; they also note that fixed costs appear higher for ecodesigned products and therefore longer-term profitability on ecodesigned products requires further study.

3.3.2 Getting Sustainable PSS in Product Development

Many perceptions on sustainable product development come from traditional product development environments, and perceive sustainability as additional criteria to be added onto traditional design criteria such as functionality, quality, features, and cost (e.g. Lu et al. 2011). There is significant research in a variety of areas closely relating to sustainability in product innovation. Recently, work was done at Imperial College focusing on Sustainable Product and Service Development (SPSD) that reviewed many approaches to sustainability in product development and resulted in an approach that emphasized functional and systems thinking (e.g. Maxwell and van der Vorst 2003; Maxwell et al. 2006). A summary of ecodesign, which emphasizes bringing ecological issues into the product innovation process, can be found in a special issue of the Journal of Cleaner Production focused on the topic (Karlsson and Luttropp 2006), as well as closely-related concepts like Design for Environment (DfE) (e.g. Graedel and Allenby 1998).

The subtle, yet complex, change required in the processes, skills and practices that are needed to actually develop and optimize products and services to deliver in a PSS business model remains a challenge (e.g. Johansson 2002; Boks 2006). Such a complex transition requires not only a new set of processes and tools, but also another set of integrated competences where sustainability and integrative skills and principles are core. Practically, such transitions take time, since people and organizations need to re-think, be (re-)educated, etc. Furthermore, the ongoing transition towards service development or service economy increasingly requires the development of partnerships and networks (Lockett et al. 2011). The more industry moves towards offering functional solutions instead of single products or services, the more complex the system of actors available to deliver such offers becomes (Krucken and Meroni 2006). To find holistic solutions that are viable in today's complex society, the concept of PSS requires multi-disciplinary approaches considering inputs from a broad range of disciplines, e.g. economics, management, environmental studies, sociology, psychology, product design and engineering (Mont and Tukker 2006).

3.3.3 Economic Aspects

Through all of the details, firms cannot continue to exist if expenditures systematically exceed revenues in the current market economy society. Consistent with the experience of the author, Berry summarizes nicely:

> *[R]esearch suggests that the underlying cultural assumptions regarding corporate environmental responsibility and environmental management are still primarily economic regardless of espoused corporate values and vision to the contrary. The firm strives to achieve lower costs and competitive advantage through conservation activities, and to avoid future liabilities and additional regulation through active environmental management policies and procedures.*
> (Berry 2004)

At a corporate level, Willard (2002, 2012) provides resources for making an economic argument for sustainability through things like improved attraction and retention of talented staff, more motivated personnel, and improved efficiency. At a product level, however, it is more difficult to make arguments with confidence that sustainability efforts will support (short term) profits. Often, when taking longer-term perspectives, risks related to possible future regulations or material availability can be used to support arguments that start from sustainability perspectives. Public perception can also be used to support economic arguments for doing sustainability-friendly things, but it still requires that economic argument to provide justification.

3.3.4 SSD and Product Development

Research at BTH has focused on bringing together a strategic sustainable development perspective with traditional product innovation approaches. Previous work suggests that there is a need for systematic integration of sustainability aspects in the product innovation process with strong support from senior management and presents a method for doing so (Hallstedt 2008). Previous work also provides detailed examples for how the FSSD can be used to design tools intended specifically for incorporating a full sustainability perspective in the early stages of product innovation and the importance of life cycle management (Ny 2009).

3.3.5 PSS and Sustainability

PSS has conceptual roots in the "functional economy" described by Stahel as:

> *[A]n economy that optimises the use (or function) of goods and services and thus the management of existing wealth (goods, knowledge, and nature). The economic objective of the functional economy is to create the highest possible use value for the longest possible time while consuming as few material resources and energy as possible. The functional economy is therefore more sustainable, or dematerialised, than the present economy, which is focused on production as its principal means to create wealth and material flow.*
> (Stahel 1997)

With the functional economy concept in mind, other early contributors to PSS literature (e.g. Goedkoop et al. 1999; Mont 2000) explore the possibilities for PSS to contribute with e.g. dematerialization (using less material or energy), decoupling (unlinking environmental pressure from economic growth), extended producer responsibility, and the role that technology can have in substituting services for materials.

Tukker et al. (2006) have explored the opportunities for environmental improvement with regard to the eight types of PSS introduced by Tukker (2004), finding that they are generally, but not necessarily, associated with improved environmental performance. Of the eight types, some have the opportunity for more significant improvement in environmental performance than others, with the function-oriented type having the most significant opportunities. This is illustrated in Figure 6.

Tukker's eighth type, functional result-oriented PSS, leads into the idea of "functional product development" described by Isaksson et al. (2009) as having the objective of "developing the solution (i.e. any combination of hardware, software, services, etc.) to customer needs that create value for the customer." This is where many see the most potential to address sustainability challenges, primarily by decoupling revenue streams from physical artefacts so that innovation can happen at a systems level higher than the artefact level (e.g. Manzini and Vezzoli 2003; Maxwell et al. 2006; Kang and Wimmer 2008; Vezzoli et al. 2012).

	Environmental impacts compared with a reference situation (product)				
PSS Type	Worse	Equal	Incremental Reduction (<20%)	Considerable Reduction (<50%)	Radical Reduction (<90%)
1. Product-related Service					
2. Product-related consultancy					
3. Product lease					
4. Product renting and sharing[1,3]					
5. Product pooling[2,3]					
6. Pay-per unit use					
7. Activity management					
8. Functional result					

[1]Renting, sharing: considerably to radically better if impacts are related to product production and the product—when traditionally owned—is used with very low intensity
[2]Pooling: additional reductions compared with sharing/renting if there are important impacts related to the use phase
[3]Renting, sharing, pooling: even higher if the system leads to no-use behavior
All: if the new business model enhances the competitive position of environmentally friendly technologies, higher improvements can be at stake (not usual and case-specific)

Figure 6: Tentative (environmental) sustainability characteristics of different PSS types. Recreated from (Tukker and Tischner 2006, p. 96).

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4 Summary of Appended Papers

Papers A and B comprise a descriptive section. These papers focus on tools for sustainable product development (Paper A) and key elements relating to product innovation more broadly within a company (Paper B).

Papers C, D, and F are of a prescriptive nature. Paper C is a case study that prescribes taking a function-oriented view in business planning in order to take advantage of sustainability-friendly product attributes. Paper D suggests some general opportunities for including sustainability in product innovation. Paper F introduces an approach for bringing a strategic sustainable development perspective into conceptual design.

Paper E is also a descriptive and exploratory paper. It first describes how manufacturing firms are pursuing services, and then explores how those services could support the realization of more sustainable PSS.

Each of the appended papers contains aspects of both strategic sustainable development and product-service systems. In Table 2, they have been designated as primary or secondary focus areas and categorized as generally descriptive or prescriptive in nature.

Table 2: Primary and secondary focus areas and the general nature of the appended papers.

Paper	Strategic Sustainable Development	Product-Service Systems	General nature of the paper
A	P	S	Descriptive
B	P	S	Descriptive
C	P	S	Prescriptive
D	S	P	Prescriptive
E	S	P	Descriptive
F	S	P	Prescriptive

P = Primary focus, S = Secondary focus

4.1 Paper A

Decision Support Tools for Sustainable Product Innovation in a few Swedish Companies

Published as:

Thompson, A. W., P. Lindahl, S. Hallstedt, H. Ny and G. Broman. 2011. Decision Support Tools for Sustainable Product Innovation in a few Swedish Companies. *3rd International Conference on Research into Design (ICORD).* Bangalore, India.

Summary

This paper explores how and where sustainability is considered in the product innovation process at six Swedish companies. A map of the overall operations and where sustainability is considered in those operations for each of the companies is related to a generic product innovation model. Brief descriptions of some tools used to support those sustainability considerations are provided. Responses regarding where interviewees see gaps with regard to including sustainability in their companies' innovation processes are also summarized.

Relation in Thesis

This paper confirms and provides further insight into a key assumption: that there is an opportunity to expand existing methods and tools to support sustainability considerations in product innovation. The study contributed to the Ph.D. candidate's view of possibilities of how and where to include sustainability aspects in traditional product innovation environments, specifically viewed through the lens of strategic sustainable development.

Results

The paper concludes that there are some, but not sufficient, methods and tools to support inclusion of sustainability aspects in the product innovation processes of these companies. It also makes the point that many of the existing methods and tools for bringing sustainability considerations into the product innovation process are based on a forecasting approach, rooted in a mindset of reducing known negative impacts. Some companies have, and more wish for, methods and tools that support them in considering a broader life cycle perspective of their products and a more proactive and strategic approach.

Contribution of Author

The Ph.D. candidate was involved from the early stages of planning the interviews, participated in interviews with three of the six companies, and led the summarizing of results and the writing process. Other authors participated in the interviews, contributed to summarizing the interviews, and reviewing and commenting upon drafts of the paper.

4.2 Paper B

Key Elements for Implementing a Strategic Sustainability Perspective in the Product Innovation Process

Published as:

Halllstedt, S., A.W. Thompson, and P. Lindahl. 2012. *Journal of Cleaner Production.* Accepted.

Summary

This paper presents identified key elements for successful implementation of a strategic sustainability perspective in a company's product innovation process. Data was collected through in-depth interviews of 20 people in six companies. The results from the interviews are divided into strengths and challenges of the companies with regard to implementing a strategic sustainability perspective.

Relation in Thesis

This paper builds on Paper A by going into more depth and detail. This paper contributes to this thesis in two main ways. The first contribution is through identification of key factors to bring a strategic sustainable development perspective into the product innovation process within an organization. The second contribution is an indication of the complexity of bringing sustainability into an organization due to the variety of places and ways in which sustainability can be incorporated.

Results

This study suggests that a successful implementation of a strategic sustainability perspective in product innovation processes requires consideration of at least four aspects in a company: (1) the entire organization, i.e. referring to elements that are relevant to the entire company; (2) processes, e.g. sustainability criteria included in the product requirement list; (3) roles/people, e.g. someone has responsibility for sustainability aspects throughout the product innovation process; and (4) tools, including the identified need for tools that: (i) introduce a systematic way for knowledge sharing; (ii) support guiding decisions in a way that also includes a long-term perspective as a complement to assessment tools; (iii) incorporate a backcasting perspective from a definition of success within principles for sustainability.

Contribution of Author

The Ph.D. candidate participated in the research design, participated in all except one of the interviews, transcribed two of the interviews, reviewed and summarized all the interviews, and was actively engaged in writing and editing. Other authors drove the research design and writing processes.

4.3 Paper C

Towards Sustainability-driven Innovation through Product-Service Systems

Published as:

Thompson, A.W., T.C. Larsson and G. Broman. 2011. Towards Sustainability-driven Innovation through Product-Service Systems. *3rd CIRP International Conference on Industrial Product-Service System (IPS2).* The International Academy for Product Engineering (CIRP). Braunschweig, Germany.

Summary

This paper explores how sustainability considerations can be better integrated into existing product innovation working environments, with an emphasis on opportunities that occur as sustainability knowledge leads to innovation through a PSS approach. Examples and ideas are discussed regarding how sustainability can drive innovation processes through PSS that companies rely upon, while also supporting global society's movement towards sustainability.

Relation in Thesis

This paper essentially presents a mid-point perspective on this research work, with an emphasis of how to use sustainability thinking to drive innovation processes. For the Ph.D. candidate, it represents a realization that to move beyond incremental sustainability improvements, more significant changes will be required than those described earlier, e.g. in Paper A.

Results

Three opportunities to consider how sustainability can drive innovation processes are presented: (1) Expansion from sustainability constraints to sustainability-driven innovation; this is because sustainability as "add-on" only serves to further constrain idea space; (2) Create value by optimizing at a broader system level. Here the focus is on looking outside of what might traditionally be considered within product development in order to identify opportunities to optimize at a higher system level; (3) Innovate the offer, not the artefact. Here the suggestion is to take a product that inherently has a sustainability-friendly attribute and innovate the business model around it.

Contribution of Author

The Ph.D. candidate wrote this paper, with other authors contributing through reviews and editing. Other authors assisted with data collection and reviewing and editing drafts of the paper.

4.4 Paper D

Benefits of a Product-Service System Approach for Long-life Products: The Case of Light Tubes

Published as:

Thompson, A. W., H. Ny, P. Lindahl, G. Broman and M. Severinsson. 2010. Benefits of a Product Service System Approach for Long-life Products: The Case of Light Tubes. *2nd CIRP International Conference on Industrial Product-Service System (IPS2).* Linköping, Sweden.

Summary

This paper extends the same logical arguments in favor of a PSS approach that have been offered by early contributors in this field by shifting the starting point of those arguments. Here the emphasis is that products designed for long-life gain competitive advantage through a PSS offer by capturing value that is otherwise distributed elsewhere in the value chain. Rather than having a regular product evolve into a PSS and then working towards longer-life, it is possible to start with a long-life product that gains competitive advantage by selling function: this is a different path to the same result.

Relation in Thesis

This study considers both environmental and economic aspects of a PSS approach. The paper uses a Strategic Life Cycle Management (SLCM) tool (now called SLCA – Strategic Life Cycle Assessment) that is based on the FSSD to show how sustainability aspects of a PSS approach can be compared to a traditional offer. The paper also discusses the value proposition, emphasizing value to the producer and value to the consumer, and showing benefits of considering both distinct perspectives during PSS development.

Results

Products designed for long-life often have significant potential for better sustainability performance than standard products due to less material and energy usage for a given service provided, which usually also results in a lower total cost. These benefits are not always clear or appealing to customers; these products are therefore at an inherent disadvantage. When the revenue base is shifted to be the function of light, there is an opportunity for a "win-win-win" for the light user, the long-life light provider and society.

Contribution of Author

The Ph.D. candidate drove this paper including developing the approach used in the paper and the writing process. Other authors assisted with data collection and reviewing and editing drafts of the paper.

4.5 Paper E

Pursuing Sustainability through Servitization in Manufacturing Firms

Published as:

Thompson, A.W., T.C. Larsson, O. Isaksson and G. Broman. Pursuing Sustainability through Servitization in Manufacturing Firms. *Journal of Cleaner Production*. Submitted.

Summary

The addition of services and pursuit of sustainability have both been driving change in the manufacturing industry for several decades. Adding these services around existing products is challenging, and firms are gaining competence and increasing capacity to deliver these services. Yet "sustainable PSS" have not been widely implemented, and this article explores reasons for this both through literature and case studies that are used to provide illustrations.

Relation in thesis

This paper takes a more critical view on why "sustainable PSS" do not appear to be implemented or achieving the sustainability improvements as one might expect given the potential benefits described elsewhere. It is framed more strongly from the industry perspective relative to earlier papers that tend to have stronger framing with sustainability aspects.

Results

Two overarching reasons are put forth for why "sustainable PSS" have not been more widely implemented. First, the implementation of PSS as such, i.e. adding services for a traditional manufacturing company, is challenging by itself. Both function-oriented solutions and co-development are fundamental to the basic concept of PSS, as well as full of challenges due to the need for business model innovation, competence development, new relationships, etc. Second, common definitions relating to e.g. "use less" or "factor x" reductions are not sufficient and not always necessary to reach sustainability. Hence a robust approach to sustainability that includes clarification of the system to be sustained, what is required for that system to be sustained, and guidance for selecting and prioritizing actions to work towards sustainability could be utilized here.

Contribution of Author

The Ph.D. candidate wrote this paper. Other authors contributed with case data and made contributions to the development of ideas expressed in the paper and with reviewing and editing drafts of the paper.

4.6 Paper F

Introductory Approach for Sustainability Integration in Conceptual Design

Published as:

Thompson, A. W., S. Hallstedt, and O. Isaksson. 2012. Introductory Approach for Sustainability Integration in Conceptual Design. *International Design Conference (Design 2012)*. Dubrovnik, Croatia.

Summary

This paper proposes an approach for integrating sustainability into the conceptual design process. It identifies and proposes solutions to two problems. First, that common sustainability criteria are not sufficiently robust, while more robust criteria are not directly applicable for use in setting requirement specifications. Second, in a design situation there is little time and data available to undertake work to integrate sustainability. Initial work has been done to complete the first step in a design project to develop a set of robust sustainability criteria that ensure a full product life cycle perspective and a comprehensive view on social and ecological sustainability. It also includes the idea of incorporating a "sustainable design space" to complement common existing "performance" and "produceable" design spaces.

Relation in Thesis

This paper follows papers A and B which suggest a need for better incorporating sustainability into product development requirement lists while also stating the importance of being able – and providing thoughts on how – to ensure that those criteria are aligned with tools, methods, and available data throughout the development process. It also picks up on ideas seeded in papers C and D with regard to using sustainability awareness to expand and then constrain design space.

Results

The paper presents six points for consideration: (1) The importance of establishing sustainability-based criteria that are both comprehensive and operational; (2) Sustainability-based criteria can be set independent of a design project; (3) Criteria alignment through design cycle; (4) Defining a "sustainable design space"; (5) Supporting designers with regard to the sustainability domain; (6) Implications of introducing "Sustainable Design Space".

Contribution of Author

The Ph.D. candidate initiated the paper following a workshop and drove the writing process. Other authors made contributions to the development of ideas expressed in the paper and with reviewing and editing drafts of the paper.

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5 Integrating a Strategic Sustainable Development Perspective in Product-Service System Innovation

5.1 How PSS can Enable Sustainability

Product-Service Systems (PSS) are generally considered to be working towards sustainability, with the clarification that it is specific categories of PSS that allow for the radical sustainability improvements that are necessary to address society's sustainability challenges in the product-related realm (e.g. McAloone and Andreasen 2004; Pawar et al. 2009). It is not that PSS as such is inherently sustainable, nor does a PSS approach necessarily reduce negative environmental or social impacts; in fact, there is nothing that guarantees that co-development of products and services is more sustainable than products and services independently. There are two primary aspects of PSS that make them attractive from a sustainability perspective: optimization at broader system levels and improved life cycle management of materials.

First, the opportunity to optimize at broader system levels that allows for reducing material and energy demands. Tukker and Tischner (2006) go into some detail around this, discussing the possibility (again, without claiming a guarantee) for product- and use-oriented PSS categories to perhaps factor two improvements (i.e. 50% reductions) in material and energy use, and for result-oriented PSS to perhaps go significantly beyond that. This is commonly discussed in literature related to sustainability and PSS, so is not further elaborated here.

A second aspect of PSS that makes it attractive from a sustainability perspective is the potential support for improved life cycle management of products, especially with regard to change in ownership of the tangible products. In product-oriented PSS, on the product end of the PSS spectrum, traditional transfer of product ownership from producer to user does not change. However, this type of PSS can benefit from services that contribute to improved life cycle management. Examples include consulting services that advise what should happen with products at end of life and recycling services that make it easier for customers to properly dispose of products.

Moving towards the service-side of the PSS spectrum, use- and result-oriented categories of PSS can be better in this regard due to the change in ownership aspects (i.e. a service-provider maintaining ownership of the product rather than ownership of the product being transferred to the customer), and thus the distribution and end-of-life phases (in addition to the use phase) of the product's life cycle. These can lead to improved collection of products at end-of-life, thus encouraging re-use and/or recycling. Theoretically these closed loops can (i) reduce demand for the net introduction of raw materials into technical systems, and (ii) keep materials within technical loops and thus not leaking into the ecological system.

These are aspects of the societal sustainability challenge (i.e. eliminating contributions to violations of basic principles for a sustainable society). They are also strategic challenges for companies, i.e. ensuring continuous availability of materials from which to make products. Furthermore, affected distribution and end-of-life systems can also support the introduction of new technologies, i.e. lighter weight materials (to reduce related energy use); less environmentally or socially harmful materials and processes; or higher-efficiency products.

It is the dual possibility of sustainability improvement together with the manufacturing industry's pursuit of servitization in order to remain competitive that makes PSS particularly interesting. Throughout interviews and workshops conducted in this research (reflected in Papers A and B, and to some extent Papers C and D), individuals would often express an interest in pursuing more sustainable products. However, their expression of that interest was often clouded by their perception that the company was primarily interested in pursuing the bottom line, and that such a pursuit of the bottom line did not allow time or space to develop more sustainable products. Since the overarching goal of this research is to contribute to the sustainable development of society, the interest of the manufacturing industry in servitization is considered as an opportunity. Since changes in methods, tools, processes and roles/organizations will likely be required to enable manufacturing firms to pursue offers with higher service content, this seems like an opportune time to also embed sustainability since it requires changes in many of the same aspects.

5.2 How SSD can Enable PSS Innovation

An SSD approach provides two specific benefits to PSS innovation: clarification of the system to be sustained and a clear definition of what it means for that system to be sustained.

Within PSS literature, there is frequent reference to the need to pursue more sustainable solutions, which is frequently translated to a need to use less material and energy, i.e. "factor X" reductions (e.g. Vezzoli and Manzini 2008). These are generally good from an SSD perspective. However, there is an opportunity to have a higher level of sophistication with what it means to be sustainable. The basic principles for global socio-ecological sustainability that are at the second ("success") level of the Framework for Strategic Sustainable Development (FSSD) are an attempt to define the line between a sustainable and an unsustainable society. The validity of this attempt can, of course, be argued, but that is outside the scope of this work. This work assumes that the principles can continue to be developed if such a need is found, as is happening related to the social system (e.g. Missimer et al. 2010). It is the logic with which the principles have been arrived at – specifically that they are both necessary and sufficient to describe a sustainable society – that is of primary interest here, and this is illustrated in Figure 7, along with some common sustainability-related indicators. These indicators are relevant to sustainability, but are not sufficient to cover all aspects of sustainability (e.g. becoming carbon neutral is not enough to be sustainable), nor are they always related to what is necessary (e.g. some carbon emissions do not contribute to violation of sustainability principles).

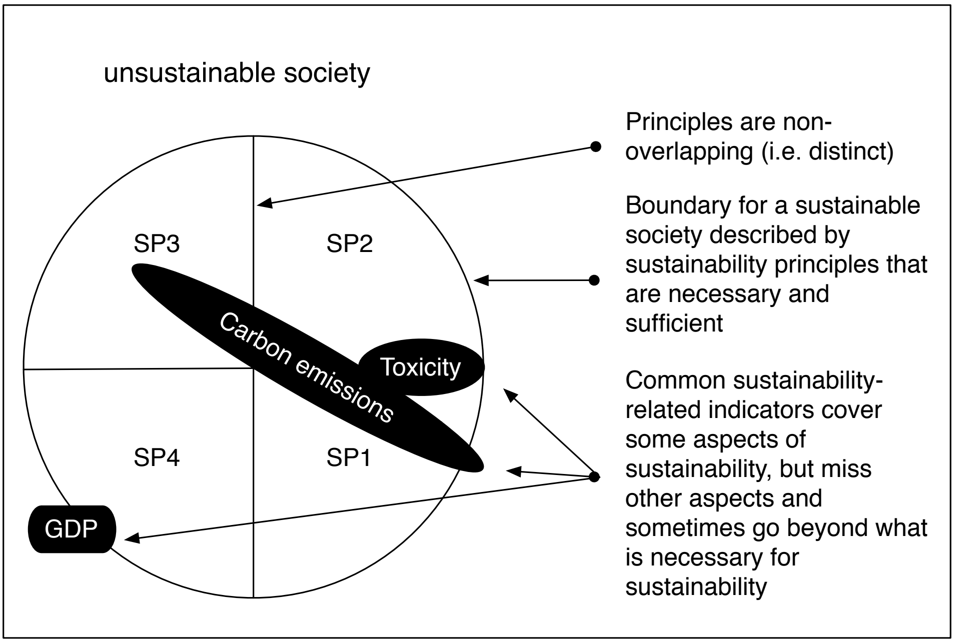

Figure 7: How some common indicators used in "sustainability" relate to boundary conditions for a sustainable society.

5.2.1 Implications for PSS Solutions

The FSSD approach is about getting to "doing no bad" (what is sufficient for a sustainable society, i.e. not degrading social or ecological systems) without eliminating consideration of any possible solutions that are "not bad" (going beyond what is necessary for society to be sustainable). The goal to use less energy and materials does not necessarily direct towards solutions that are in line with sustainability, and may prevent consideration of solutions that are potentially more in-line with sustainability principles (illustrated in Figure 8). An example illustrates this point: if a building is heated using fossil-based fuels, then the guideline of "use less energy" is appropriate. However, if a different energy source can be utilized that has no contributions to violations of sustainability principles, e.g. passive solar energy, then using more energy can be okay from a sustainability perspective. This suggests that factors such as the form of energy used (liquid fuel, electricity, heat, etc.), the primary energy source (fossil fuel, solar, tidal, nuclear, or derivative of these), and the time of use (e.g. during peak times, when the sun is shining, or continuously) can lead to energy use that has fewer contributions to violations of sustainability principles than the simple guideline of "use less."

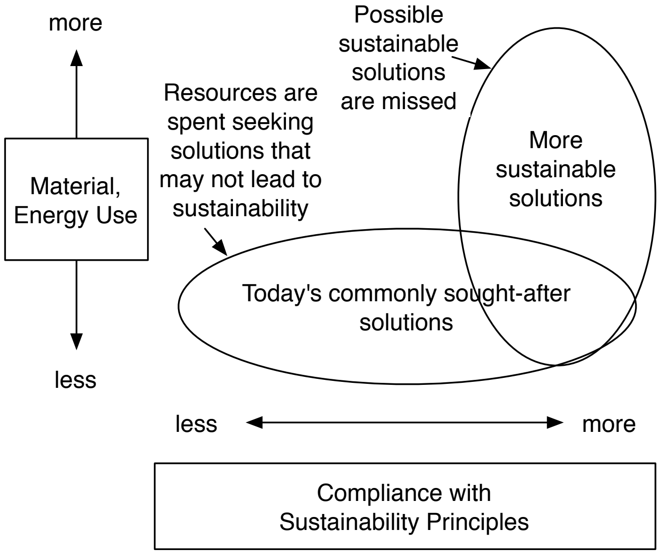

Figure 8: Comparing solutions space commonly explored today based on general guidelines to use less with possible solutions that aim to align with principles for a sustainable society.

5.3 Moving forward with SSD in PSS

Considering the literature presented in section 3.3, especially the work of Baumann et al. (2002), Knight and Jenkins (2009), and Bovea and Perez-Belis (2012), it seems critical to consider how sustainability aspects could better integrate with other on-going work in the product innovation working environment. To that end, two concepts are mentioned directly that can help to do this: the move to integrate services, and the similarities between an SSD-based approach and set-based approaches to product development. Each is explained in more detail here.

5.3.1 Services as Starting Point into PSS

There are various reasons for why manufacturing firms have pursued services, and they have faced several challenges in doing so (section 3.2.5). Despite the challenges, it seems that there are opportunities to use the manufacturing firm's interest in services – typically the more familiar "add-on" services that would be categorized as product-oriented PSS – as momentum for moving into other categories of PSS that have increased potential for supporting society's movement towards sustainability.

The servitization that is coming out of the PSS arena differs from the earlier servitization literature stream in some key ways. First, PSS leads towards co-development in which services are central in the design process rather than merely "add-ons" to manufactured products (see Figure 9). It is difficult to discern a clear point in time when this subtle change in thinking occurred, but it is clear that the mainstream servitization literature from the 1980's and 1990's focuses primarily on adding on services to manufacturing products, while the PSS literature of the 2000's considers this "service add-on" as but one type of several possible combinations of products and services. The difference is illustrated in Figure 9. Oliva and Kallenberg (2003) observe this difference between "servitization" and PSS: "*Most manufacturing firms provides services… [t]hose services, however, have traditionally grown in different parts of the organization, are fragmented, and considered an unprofitable necessity to sell the product.*" That view appears to be evolving, e.g. from servitization as an "unprofitable necessity" (i.e. a cost) to a source of revenue (Oliva and Kallenberg 2003), and is consistent with more recent findings (e.g. Neely et al. 2011).

Even though a PSS approach does not guarantee a more sustainable solution than products without service (Christensen 2007), the main interest in PSS from the sustainability perspective according to the PSS literature is in moving towards function-/result-oriented PSS because this is where the big opportunity for decoupling firm revenue from physical resource flows is perceived to be. Paper E suggests that PSS categories that shift ownership can also be interesting in order to increase incentives for more sustainable approaches to life cycle management of materials.

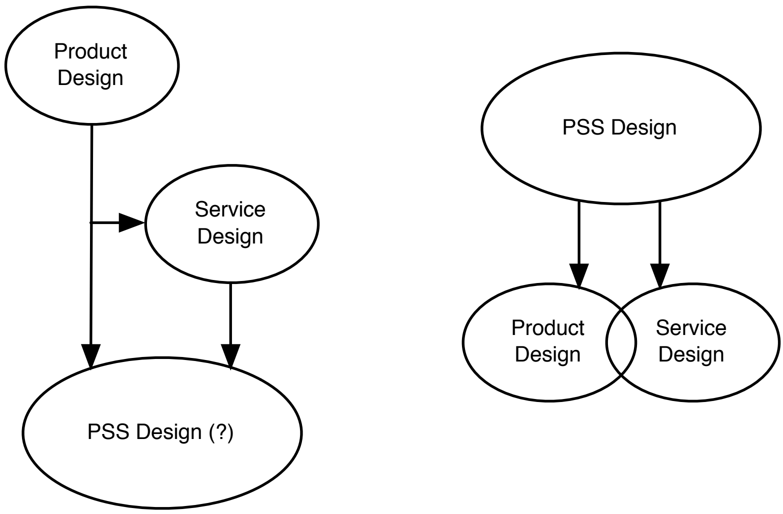

Figure 9: Manufacturing firms now commonly add services to existing products to arrive at product-oriented PSS (left). To open up to more significant sustainability opportunities, firms should consider to move towards designing solutions at the PSS level first, and from there co-develop the products and services required (right).

Because of challenges to pursuing services, there is a risk that a firm might not continue through to use- or result-oriented PSS, or it might find the economic aspect more attractive to stay with product-oriented PSS. The other side of this, however, is that the as the firm develops the competence and capacity to deliver services, it may continue to find competitive advantage in moving farther into use- and result-oriented PSS.

5.3.2 Bringing Together Set-based Approaches

The tangible products that are included in the PSS can benefit from SSD-enabled development processes. This is true regardless of whether the product is developed before services are considered, or if the product is considered together with services.

With this in mind, an approach is presented in Paper F, and summarized here, that is inspired by the work that e.g. Sobek et al. (1999) and Ward et al. (1995) did to explore set-based product development at Toyota in the 1990s (and was briefly described in Section 3.2.3). The exploration of solution space and setting boundaries before convergence on a specific design target aids in identifying potentially better options. This is related to "*bringing in and aligning a sustainability perspective throughout the design process*" (e.g. key element 2 identified in Paper B). The premise is to more clearly define a solution space before deciding on a design target – in the Toyota context it was often described in terms of integrating with suppliers, i.e. the intent was to identify the solutions that suppliers had the capability to provide that would intersect with Toyota's general targets.

Instead of using the supplier's capabilities and Toyota's desires as the solution sets to be integrated, Paper F introduces "performance design space", "produceable design space", and "sustainable design space," with the latter being bounded by sustainability principles since those principles describe the boundary between what is sustainable and what is not sustainable at a societal level. These three are not necessarily the only sets to be included; they are used to illustrate the concept (see Figure 10).

As alluded to in Paper F, it may not be possible to find an intersection of the required sets, i.e. able to be produced, meets performance needs, and complies with sustainability principles. Therefore, a "Sustainability Compliance Index (SCI)" could be introduced that is similar in many ways to the concept of Technology Readiness Levels (TRL). TRL is commonly used in some advanced industries to communicate the development state of technology. The SCI would essentially communicate progress towards alignment with sustainability principles. It could be constructed of indicators that strike a balance between being easy to use and readily available while also covering as much as possible of what is necessary to be sustainable (i.e. covering the entire sustainability circle in Figures 10 and 11).

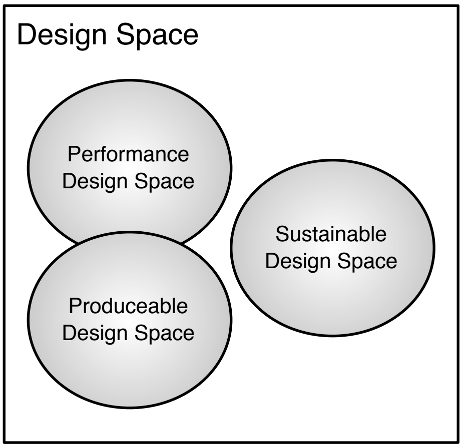

Figure 10: Introducing "Sustainable Design Space" described by boundary conditions for a sustainable society into the Design Space.

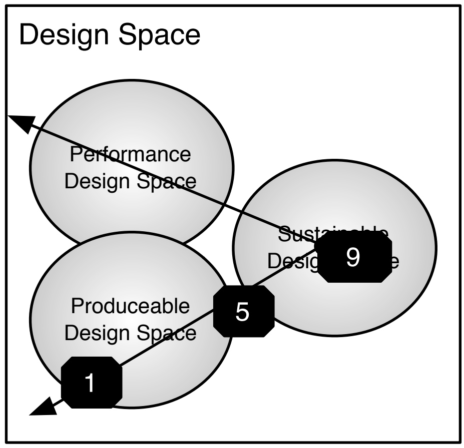

Figure 11: Introducing a "Sustainability Compliance Index" to assess progress towards alignment with the "Sustainable Design Space".

Such an SCI would incorporate key aspects of the FSSD in a few ways. The system (level 1) to be sustained is clearly defined via the boundaries that are set for the sustainable design space, i.e. those boundaries are set for the global socio-ecological system. The success level (2), with the sustainability principles, is included by virtue of being the boundaries of the sustainable design space. The strategic (backcasting) perspective (level 3) is included by supporting movement towards alignment with the sustainable design space, the boundaries of which are defined by sustainability principles. That is to say that the SCI levels (e.g. with 0 being no consideration of sustainability and 9 being no contributions to violations of SPs) would be structured so as to lead towards sustainability in a way that considers the FSSD's strategic guidelines, i.e. a solution being (i) a flexible platform for forthcoming steps that, taken together, are likely to bring society and the organization the defined success, by striking a good balance between (ii) direction and advancement speed with respect to the defined success and (iii) return on investment to sustain the transition process.

The general approach appears to be applicable whether it is an artefact being developed or a PSS solution. The sets to be integrated may need to be adapted or additional sets added in order to be utilized for PSS development, e.g. the capacity to delivers services might be added alongside the ability to produce the artefacts.

Second, since PSS often relies upon extended value chain collaboration, the applicability of this approach to that extended collaboration is a question. Toyota's experience suggests that this set-based approach is effective in working with a supply chain for producing physical goods. One can imagine such an approach would also be effective for developing PSS provided that a shared language enabling effective communication could be found.

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6 Contributions

This work aims at supporting the inclusion of a strategic sustainable development perspective in the product innovation process by articulating how sustainability can provide constraints and at the same time open up for new possibilities that can guide the innovation process.

This work contributes to both understanding with regard to theory regarding how innovations can occur through product-service systems that support working towards a sustainable society, both within the broader research field, as well as how to apply that understanding to the state of practice in industry today in order to realize more sustainable PSS.

6.1 To the Research Field

This research makes these contributions to the field:

- Clarification that the pursuit of sustainable PSS needs to have an operative definition of sustainability. This should take a full global socio-ecological sustainability perspective, rather than only striving for reductions in material and energy use in a PSS.
- Exploring if and how PSS concepts can support society's transition to sustainability beyond the more common acceptance of using PSS to reduce use of materials and energy.
- Awareness of the distinction between PSS that result from efforts to add services to existing products and PSS that are initially designed at a PSS-level, allowing for optimal combinations of products and services to be co-developed.
- Making the logical connection between the approach to defining the design space in set-based design and describing a "sustainable design space" bounded by sustainability principles that are necessary and sufficient to describe a sustainable society.
- A proposal for integrating sustainability in the conceptual design process that bridges the robustness of a strategic sustainable development approach and the need to fit into an industry design cycle.

6.2 To Industry

This research supports industry by:

- Showing how sustainability is currently included in some companies' product innovation processes, along with ideas for how to further integrate sustainability considerations into their daily work. This includes expanding the scope of common environmentally-focused work to include the broader product life cycle, and the possibility of doing so through a PSS approach.

- Sharing a case study showing some insight into the possibility to reconsider an existing physical product in a PSS approach to innovate the business model in order to take advantage of existing sustainability-friendly aspects of the product.
- Providing context with regard to how the services that companies are implementing fit into a broader PSS and/or sustainability-oriented picture.
- Encouraging the utilization of sustainability knowledge to open up new solution space, rather than only constraining existing concepts by adding on sustainability criteria.
- Respecting the challenges for manufacturing companies to develop service competence and delivery capacity while at the same time encouraging development of those services in a way that supports society's movement towards sustainability.
- Proposing an initial approach for how sustainability could be brought into a product innovation process through set-based design. This includes a "Sustainability Compliance Index" to guide the development of solutions towards alignment with sustainability principles.

7 Conclusion and Future Work

7.1 Conclusion

Methods and tools for including sustainability today in product innovation working environments can be improved by including a broader life cycle perspective together with a more proactive and strategic approach that utilizes competence based on a strategic sustainability perspective. In addition to improving those methods and tools, there is a need to also consider other aspects within the product developing organization; specifically (1) organizational management aspects that are relevant to the entire company, (2) processes that govern how and where sustainability criteria, methods, and tools are used, and (3) the roles that people have, e.g. to ensure that someone has responsibility for sustainability aspects throughout the product innovation process.

A case study of long-life light tubes presents the possibility for an extended value chain perspective to contribute to identifying opportunities to capture value through innovations in business models around products with sustainability-friendly attributes. Further, sustainability can support driving innovation to find new solution space, rather than only constraining current solution space. This can lead to identifying opportunities to optimize at broader system levels, enabling cost reductions or increased revenues.

The pursuit of product-service systems offers an opportunity for the manufacturing industry to contribute to society's movement towards sustainability. However, a PSS approach does not ensure that the result will be more sustainable solutions. The shift that is occurring as firms invest in competence and capacity to deliver services opens up the opportunity to develop PSS that are more likely to lead to more significant sustainability improvements by e.g. supporting the closure of material loops and optimizing at broader system levels that allows for reduced material and energy use.

A strategic sustainable development perspective can contribute to the successful and more sustainable innovation of PSS in two ways. First, by clarifying the concept of sustainability – both what is to be sustained (the global socio-ecological system), and what it means to be sustained (i.e. not systematically degrading those systems and the basic mechanisms by which that degradation happens). Second, by utilizing that clarification to provide support for designing PSS solutions that contribute to the success of PSS providers. This is demonstrated in an approach proposed for integrating sustainability aspects into conceptual design. This proposal highlights the opportunity to use a strategic sustainable development approach that defines boundary conditions that are sufficient, yet necessary, for a sustainable society as a more sophisticated approach to including sustainability aspects in product development.

7.2 Future Work

This research opens up several avenues for future research work. One avenue follows from the case study presented in Paper C to explore how sustainability-friendly PSS can be considered from multiple perspectives in order to find solutions that are economically and otherwise attractive to all actors in the particular PSS network. During the course of this research many ideas for more sustainable solutions were identified, but often the challenges of implementing these solutions in the current approach to business are too daunting to be overcome. Research is needed to better understand and identify solutions to these implementation challenges, and especially to consider if and how the transition that manufacturing firms are making into services can be continued into the categories of PSS that are believed to have more sustainability potential.

Another avenue could follow from Paper F by implementing the proposed approach to integrate sustainability in conceptual design utilizing set-based approaches. Further, to consider how such an approach might be utilized along a value constellation for the co-development of PSS among networks along the lines of how Toyota uses such an approach with its suppliers.

The sustainability potential of various types of PSS can be further considered. While much literature points to the opportunity that result-oriented PSS provide to open up to “system” level innovation, this research suggests that use-oriented PSS can also be supportive of sustainability because of the change in ownership of materials throughout the product life cycle. More evidence to enable understanding around both of these would benefit the scientific community and industrial practice.

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Paper A

Decision Support Tools for Sustainability in Product Innovation in a few Swedish Companies

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Decision Support Tools for Sustainability in Product Innovation in a few Swedish Companies

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Abstract

Companies are finding that customers increasingly demand "sustainable products" while also noticing economic benefits from eco-efficiency and other sustainability-related design approaches. Employees making product-related decisions need support tools to incorporate sustainability considerations – both at strategic (e.g. regarding product lines to develop) and operational levels (e.g. detailed design). This paper presents the results from a set of interviews that explored where and how sustainability considerations are taken into account in the product innovation processes of six Swedish companies. Results are presented as a map of the overall company operations in relation to a generic product innovation model, followed by a map of the places where sustainability considerations are made in that model. Some of the tools that are used to support those sustainability considerations are also briefly described. The conclusion is that there are some, but not sufficient, tools and methods to support inclusion of sustainability aspects in the product innovation processes of these companies.

Keywords

sustainability, product development, innovation, tools

1 Introduction

1.1 Sustainability Challenges and Product Innovation

The major global sustainability challenges now facing society, e.g., climate change, access to potable water, biodiversity loss, etc. provide cause for major concern with the long-term viability of human society (Steffan et al. 2004). Product innovation is a particularly critical intervention point for the transformation of society towards sustainability. Current socio-ecological impacts over product life-cycles are evidence that current practices are insufficient. Previous studies have focused on environmental aspects in product development (e.g. Baumann et al. 2002; Byggeth and Broman 2001; Maxwell and van der Vorst 2003; Simon et al. 2000; Steen 1999; Wenzel et al. 1997), including case studies with companies in Sweden (e.g. Andersson and Ohlsson 1999; Tingström et al. 2006). This study differs in two ways from these studies: first, by utilizing an alternative approach to sustainability considerations that extends beyond a focus on known environmental issues (presented in section 1.2), and second, by using a general model of the product innovation process to identify where in the product innovation process sustainability aspects are considered (presented in section 1.3).

1.2 A Framework for Strategic Sustainable Development

This study uses a framework for strategic sustainable development (FSSD) to provide an underlying framework to keep the ultimate goal of socio-ecological sustainability in focus. This FSSD emphasizes that for human society to be sustainable, it should stop systematic destruction of the ecological and social systems that it depends upon (Broman et al. 2000; Missimer et al. 2010). This differs from some other working definitions of sustainability, which often suggest that "less bad is sustainable," e.g. products that use less energy or less water or emit less CO2 are "sustainable products" (Glavic and Lukman 2007). This FSSD-based sustainability perspective has previously been integrated into product development procedures and processes (Byggeth and Broman 2001; Hallstedt 2008) and one study incorporates the FSSD's basic principles for socio-ecological sustainability into the main steps of life cycle assessment to then support product development (Andersson et al. 1998).

1.3 A Product Innovation Model

This study uses a model of a generic product innovation process from Roozenburg and Eekels (1995) (Figure 1) to guide the interviews. This model distinguishes between product development and innovation, such that product development is part of – but not the entire – innovation process. This model also distinguishes processes from the result of the processes. When exploring where tools are used, this model helped to differentiate between process-oriented tools (i.e. tools used during a process) and assessment or analysis tools (tools used to assess the outcome after a process has been completed).

1.4 Study Purpose

This study addressed the question: how and where is sustainability considered in the product innovation process at some different companies? Results from this study contribute to an initial descriptive phase of an ongoing project described in (Ny et al. 2008), and will be used to inform opportunities to better: 1) incorporate sustainability into the product innovation process, 2) connect strategic and operational levels in companies, and 3) develop specific methods and tools to support the previous two points. This study is guided by the extensive literature study by Baumann et al. (2002), specifically with regard to how management, environmental, and product innovation issues are integrated, as well as where in the product innovation process various tools are used to consider both management and engineering perspectives.

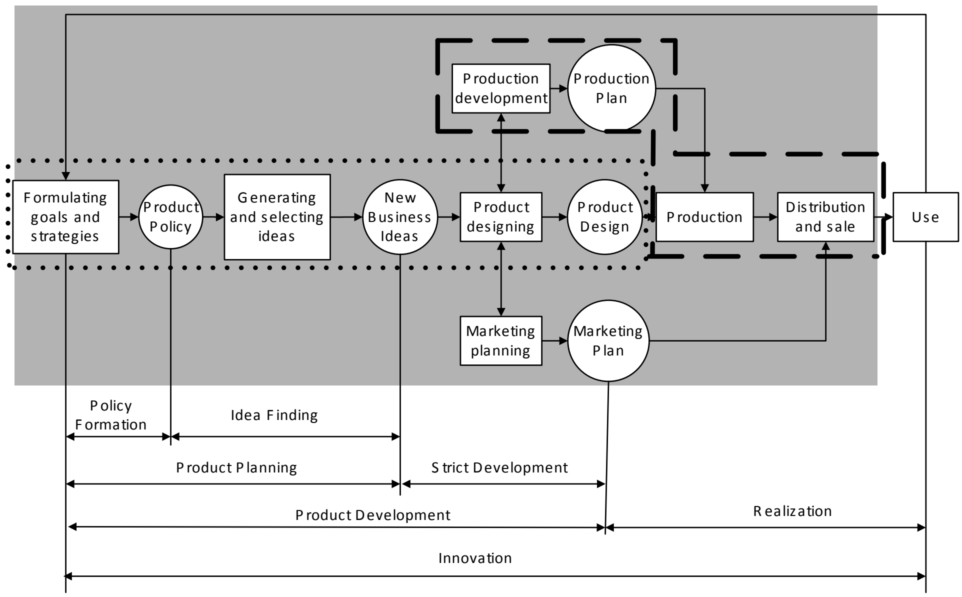

Figure 1: Operational activities at the participating companies mapped onto a generic product innovation diagram (adapted from Roozenburg and Eekels 1995). Four companies (A,B,C,F) work in the shaded areas, while one (E) focuses in the area of the dotted line and another (D) focuses in the area of the dashed line.

2 Research Approach

2.1 The Companies

Six companies that were interviewed for this study:

(A) A producer of light tubes that last about four times longer than average tubes. The company has approximately 200 employees and an annual turnover of €40M. One product engineer and the environment/quality manager were interviewed.

(B) A manufacturer of compaction machines with approximately 800 employees and an annual turnover of €230M. The product development manager was interviewed.

(C) A company that develops, manufactures, and sells adaptable sealing solutions for sealing around cables or pipes that pass through walls. They have approximately 450 employees and an annual turnover of €95M. The environmental manager and two product developers were interviewed at this company.

(D) A recycler of electronic materials with approximately 150 employees and an annual turnover of €22M. The plant manager was interviewed.

(E) A product / technology development support company that has around 4000 employees. Four people were interviewed: Environmental Manager and Feature Specialist, Feature leader for the Environment and Fire Safety, Purchasing Director, Product Development Manager

(F) A producer of jet engine components that has around 2300 employees and an annual turnover of around €465M. One project manager, one product development engineer, and the environmental impact specialist were interviewed.

2.2 The Interviews

Between one and four people working with product innovation or environmental management systems were interviewed at each of the six companies during 2009. An interview guide with three sections was used to perform semi-structured interviews. The questions in that interview guide were sent to the interviewees two weeks prior to the interviews. Four researchers from BTH were involved in these interviews, with between one and three involved in each interview. The sections were as follows:

1. Company product innovation processes compared to the model: Using the Roozenburg and Eekels diagram of the product innovation process (shown in Figure 1), a comparison was made between where the company is working and where the company is including sustainability. First, it was determined where the company sees itself working within that diagram, e.g. is it mainly focused on product development (without production), is it mainly focused on production (without the development), or does it focus somewhere else? This is presented in section 3.
2. Where sustainability is considered in the company's process: Where, with regard to the innovation model, are sustainability-related decisions taken? (presented in section 4), and what sustainability-related tools are used, and where are they used? (presented in section 5).
3. Sustainability-related opportunities: Where, with regard to the innovation model, do the interviewees feel that additional tools would be helpful, or

where should additional decisions be taken with regards to sustainability considerations? (Presented in section 6).

3 Company Product Innovation Processes Compared to the Model

Primary activities in four of the companies (A,B,C,F) essentially covered the entire innovation diagram, i.e. each of these processes at the companies is addressed in the daily work. This is represented by the shaded area in Figure 1. The other two companies (D,E) had more targeted areas in daily operations. One is primarily a technology development company (E) and does not produce any physical products; this is indicated by the dotted line in Figure 1. Company (D) works with electronic waste, and as such is not involved in product innovation, though the company does have its own production plan regarding how to process the electronic waste.

Interviewees generally agreed that the Roozenburg and Eekels model was a good enough generic representation of their processes. One modification suggested by several of the companies was that "Product designing" and "Marketing planning" often have a significant influence on "Generating and selecting ideas", so there could be a link back to that box.

4 Where Sustainability Aspects are Considered

All six companies have a sustainability aspect that plays a significant role in their product policy, as will be described in 4.1. However, none of these companies incorporated tools or decisions that suggested they include a strategic sustainability perspective in their complete process (i.e. a conscious step-by-step approach towards eliminating its contribution to global social and ecological un-sustainability while improving its competitiveness).

4.1 Policy Formation

All five of the companies that had daily activities in the policy formation area (A,B,C,E,F) had something in their product policy related to improving the sustainability performance of their products. For example, Company A's product inherently has an attribute that is generally considered positive from an environmental perspective: it is designed for long life times, so that fewer of the light tubes and thus the life cycle activities associated with production, transport, end-of-life, etc. are used. Company B has a strong focus on reducing energy use in their machines. Company C develops "sealing solutions" that are intended to improve safety and efficiency of the structures they are used in. Company E has 32 product features that must be addressed for the products they develop; five of these are specifically focused on sustainability-related issues. Company F has a strong emphasis on reducing component weight in recognition that the lighter their components are, the less fuel the airplanes will require.

In addition, two of the companies (E,F) have "environmental care" as one of their three core values. While it is not clear how this affects the product innovation process, these core values were repeated multiple times by interviewees when they were asked about sustainability. They also stated that they have environmental issues in their minds during their daily work, and suggested that is largely influenced by these core values.

4.2 Idea Finding

Companies used the sustainability aspects from their product policies as inspiration for idea finding. For example, long-life, light-weight, or low energy use over the life cycle were motivating factors in the generation/selection of ideas, and in the assessment of new business ideas. It was not clear, however, if or how a more comprehensive or strategic sustainability perspective was explicitly included in any of the companies during idea finding, either for the generation of new ideas or for the evaluation of ideas.

4.3 Strict Development

There was consistently good alignment between product policy and the strict development phase for those sustainability considerations that were included in the policy formation phase, i.e. if something was stated in the product policy, it was taken into account in some way during the development phase. Similarly, if something was lacking in the product policy, it was not likely to be considered in the development process. In short, sustainability aspects were not added for the first time in the development phase.

4.4 Realization (Production, Distribution, and Sale)

All companies have an environmental management system (EMS), which is typically focused on facilities and operations management during production. Several companies also stated that they considered impacts outside of their own facilities, such as the distance between suppliers and their own facilities when choosing suppliers in an effort to reduce transports for both economic and environmental reasons.

Social aspects of sustainability were often mentioned here, also, with regard to the company's own production facilities, e.g. worker exposure to hazardous emissions, high noise levels, or ergonomically unfriendly conditions. With the two larger companies (E, F), there was explicit reference to also considering working conditions at their suppliers.

4.5 Realization (Use)

All of the companies in this study had a life cycle perspective of their product that included the use phase, thus they saw value in improving the sustainability performance of their product during its use phase even though the product would no longer be in the company's possession. At the same time, the sustainability aspects that companies considered were usually partially aligned with other considerations in the process, primarily legislation and cost. For example, fuel efficiency is a significant consideration when developing products at several companies both to comply with legislation and to lower operating costs for their customers. Of course, fuel efficiency is also commonly considered a sustainability aspect.

One of the companies (E) had done a significant amount of work to determine the life cycle environmental impacts of their product, and had taken steps to develop key indicators to address the major environmental impacts. This resulted in five features that were included in the overall 32 product features that were set for each development project. The other companies had made educated estimations of sustainability impacts across their products' life cycles, though they seemed less thorough in their identification of the key sustainability impacts.

5 Tools to Support Sustainability Considerations

Here tools are listed that were identified during this study, along with a brief description of how they were being used. During these interviews, the interviewees showed relatively limited tools or decision support in the area of social sustainability. Additional tools are used for other, though sometimes related, purposes; e.g. prioritization matrices, computer-aided design (CAD) and other simulation tools, etc. Focus here is on those tools that are more directly and distinctly connected to sustainability.

5.1 Material Lists

All of the companies had some type of guidance for material choices in the form of a list. These lists were typically based on substance lists directly from legislation such as Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and customized specifically for the company. They often took the form of lists of "banned substances" that should not be used at all and a list of "substances to avoid" that should only be used in special circumstances or with the intent of phasing the substance out. Sometimes these lists applied only to substances that would be used in products, and other times these lists applied also to substances that might be used in the production process. Other material lists include PRIO – a web-based tool developed and maintained by the Swedish Chemicals Agency – to work towards reducing risks to human health and the environment. Companies also stated that they often must comply with requests from customers to not use particular substances. Nearly always, these material lists were used in product designing and often also for verification after the product design was finalized.

5.2 Environmental Management System (EMS)

All of the interviewed companies had an Environmental Management System (EMS) following ISO 14001. The EMSs were mainly used in connection with production to structure and organize the companies' work regarding known environmental impacts like reduction of emissions, substitution of chemical, and reduction of transport.

5.3 (Product-based) Environmental Impact Assessment (EIA)

Three of the six companies (C,E,F) used Environmental Impact Assessments (EIA) to assess their products' environmental impacts. These EIA tools were company specific, and vary somewhat in complexity and completeness with regard to both environmental impacts that were considered, and to the extent that the product's life cycle activities were addressed. Common among the companies is that the EIA was mainly used late in the product development process to assess already developed concepts or products where many design decisions had already been taken. Thus, the tool was in the "product design" circle of the product innovation model (and not the "product designing" box), and had relatively little impact on the development of the current product. Learning from the EIA, however, was sometimes utilized in significant ways to innovate in future development projects.

5.4 Life Cycle Assessment (LCA)

Two companies (E, F) have in their product development process the option to conduct an LCA on their products after they are designed in order to verify environmental performance. Two other companies (A,B) do not currently use LCA, but would like to explore its use for comparing new products with existing or older products to ensure that newer products do have an improved environmental performance or in order to have a better understanding of the relative environmental impacts of various aspects of their product. Company (C) expressed interest in LCA-like approaches to better understanding the environmental consequences of their product, but were mostly interested in the life cycle approach, not LCA specifically.

6 Sustainability-related Opportunities

Interviewees were asked about the sustainability-related gaps that they saw in their companies; this section presents a summary of their responses.

6.1 Use of an LCA-based Tool

Three companies (A,B,C) expressed an interest in having an LCA-based tool that would enable them to quantitatively compare product concepts, as well as to compare existing products with new products to see if they have improved sustainability performance. As noted above, two of the companies were already using LCA tools.

6.2 More Information about Early Life Cycle Stages of Materials

There is a need for more data regarding the sustainability impacts from early life cycle stages of materials. A distinction can be made between general data regarding sustainability impacts for a type of material (e.g. aluminum requires X% more energy than steel to produce) and specific data from a company's own supply chain. While access to and use of this information varied greatly among these six companies, all were interested in having more data.

6.3 Clearer Guidance During Idea Generation

Understanding that the only concepts that can be developed are those that are thought of during idea generation, one interviewee suggested that it would be helpful to have more sustainability-focused thinking during the idea generation. Interviewees at other companies echoed this to greater or lesser extents.

6.4 Support in Connecting Sustainability Aspects to "The Bottom Line"

Though suggested in different ways by different companies, there is clearly a need for evaluating how the consideration of sustainability aspects during product innovation can influence the economic success of the company. To one company (C) this meant showing how a focus on sustainability issues could directly reduce costs or lead to improved efficiency and production. Another company (B) talked about this with regard to the cost of operating their product, with the explicit assumption that if they could show reduced life cycle costs, this would lead to more success for the company.

6.5 Life Cycle Consideration of Other Impacts of Substances

The electronics recycling company (D) pointed out that many companies have lists that guide substance selection, and that often those lists are directly or indirectly based largely upon known environmental impacts. The interviewee said that there are other substances that might not be toxic, but that they can cause other "problems" in the material life cycles, e.g. with regard to the recyclability of other materials. He suggested that material guidance lists could be adapted so that they guide towards the use of materials that have more favorable life cycle attributes, e.g. are more easily recycled.

7 Discussion

Most of the decision processes and tools described by the companies were based upon known environmental impacts. In some ways this is considered to be the most practical, i.e. why worry about something if it is not known to be a problem?

On the other hand, increasing dependency on technologies that are not known to be 'safe' can lead to future problems (Byggeth and Hochschorner 2006). For example, the material lists used by the companies in this study are mainly intended to avoid using materials that have known environmental impacts and materials that are prohibited by legislation. Material lists that can be used for sustainability considerations also could consider other socio-ecological aspects, e.g. material scarcity, working conditions for people involved in the material's life cycle, and more directly: materials that are not currently known to cause problems, but are also not known to be 'safe'. In line with the above-mentioned FSSD, a precautionary approach is more strategic, especially given the rapid development and increasing pace at which new technologies are implemented and this necessitates ensuring that today's solutions do not lead to future problems.

Identification of key sustainability features in product requirements is an example of how to insert the sustainability aspects in an operational way. One of the six companies (E) has undergone a rigorous process to identify key sustainability features that it can then include at the requirements level. This process was specifically focused on identifying sustainability features, and resulted in five features that insert the sustainability aspects in an operational way into the workspace of the designers and engineers. These requirements must be set and met during product development. Several of the other companies have included sustainability-related aspects at the product policy level. This often translates into one (possibly more) specific requirement that also comes into the workspace of the designers and engineers. With these other companies, the selection of these key aspects at the product policy level appears to be less rigorous from only a sustainability perspective, and instead more of a combination of what is perceived to be good for both socio-ecological sustainability and economically for the company and its customers. This is not to say that one approach is better, but only to acknowledge a different approach and raise the question for possible further exploration.

There are opportunities for knowledge and experience from working with a company's environmental management system (EMS) to support product innovation, e.g. to inform material and process selection during product development. EMSs are often in place in order to ensure compliance with legislation regarding substance use and handling, and these systems are reviewed periodically in order to ensure that the company keeps the certificate.

All of the companies, to a greater or lesser extent, use a forecasting mindset that suggests that the main negative environmental impacts should be identified and reduced. This is a good approach when there are significant opportunities with "low-hanging fruit" – opportunities for major environmental improvement in the short term. However, a different approach is needed when these "low-hanging fruit" have been "harvested" and it is desirable to continue to advance the way in which sustainability is used to drive innovation. In order to continue to find significant sustainability improvements, it is possible to use the FSSD approach to look to different system levels and explore opportunities for optimization and innovation. These opportunities bring new challenges with regard to how companies collaborate across value chains.

Using a general model of the product innovation process to map where various tools or methods are actually used to consider sustainability aspects in company processes is expected to aid in the continuation of this research project with its aims as described in section 1.4.

8 Conclusions

This study maps sustainability considerations of six companies on a general model of the product innovation process, and shows how all six companies have taken steps to consider sustainability aspects through the tools used and decisions taken during their product innovation processes. However, there is significant opportunity to better incorporate tools and decisions that demonstrate a strategic sustainability perspective throughout the process that will allow for an intentional step-by-step approach towards eliminating its contribution to global social and ecological un-sustainability while improving the company's competitiveness.

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Paper B

Key Elements for Implementing a Strategic Sustainability Perspective in the Product Innovation Process

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Key Elements for Implementing a Strategic Sustainability Perspective in the Product Innovation Process

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Abstract

This article aims to present identified key elements for successful implementation of a strategic sustainability perspective in the early phases of the product innovation process. An in-depth interview study in six companies within the same corporate group has been undertaken together with a review of literature, previous research and company documents to evaluate if and how a strategic sustainability perspective has been successfully implemented in the day-to-day basis in the product innovation processes of the studied companies. The results are divided into strengths and challenges of the companies with regard to implementing a strategic sustainability perspective in the product innovation process. From this research, eight key elements for successful implementation of a strategic sustainability perspective have been identified. These elements are divided into four categories: organization, internal processes, roles, and tools. It is believed that incorporating these key elements into product innovation processes will encourage a company to have a strategic sustainability perspective, which will support the company's long-term success.

Keywords:

strategic, sustainability, implementation, product development, innovation process

1 Introduction

There is a societal need for accelerating change towards sustainability (National Research Council 2002). Product development and manufacturing industries have an important role in the transformation of society towards sustainability (Gaziulusoy et al. 2012). Within the area of product innovation, there are several different activities for this to happen, for example eco-labeling, environmental management systems (e.g., ISO 14001), environmental legislation, extended producer responsibility, corporate social responsibility (CSR) and guidance for social sustainability (e.g. ISO 26000). Several incentives function as driving forces in this development, e.g., an improved corporate image, increased profitability, energized employees (Willard 2002; Nguyen and Leblanc 2001; Roberts and Dowling 2002; Neville et al. 2005). Tougher consumer requests, stricter legislation and resource constraints can also help to speed up the adjustment of industry operating in a more sustainable society (Ammenberg and Sundin 2005; Spangenberg et al. 2010; Testa and Iraldo 2010).

From the global perspective, the innovation and design of products, together with incentives at a societal level, is a critical intervention point in the transformation of society towards sustainability (Tukker and Jansen 2006; Tukker et al. 2008; Petala et al. 2010). A product's socio-ecological impacts, positive and negative, throughout its life cycle are largely determined by decisions during early product development phases (McAloone and Tan 2005).

From a manufacturing enterprise perspective, awareness of the global activity is essential to ensure long-term business success. Risks and opportunities related to resources (e.g. energy, water, materials), changes in labor patterns, improved working conditions, etc., become more relevant to decisions in the product development process to ensure product success. Thus, it is imperative that rigorous, practical and readily shared methods and tools are developed for early product development phases to bridge the gap between today's innovation and design approaches and tomorrow's global needs. However, the global society's overuse of resources and increasing socio-ecological impacts caused by production, distribution, use and disposal of products indicate that current methods of decision making for product innovation and product design are insufficient. Current methods and tools are important but are lacking for the necessary and substantial change of the products that result from existing product development practices (Byggeth and Hochschorner 2006). The emphasis is often on the senior management's responsibilities of setting the main direction for product development, assuring that suitable methods and tools are actually used, allocating resources appropriately, and assuring communication through all levels of the organization (McAloone 1998; Lindahl 2005).

Thus, if manufacturing enterprises truly want to support sustainable development, it is important to do the following. First, to have a common view on sustainability

(Broman et al. 2000, Johnston et al. 2007). Second, to coordinate and integrate tools and methods for sustainable product development in the overall decision-making process (Boks 2006, Johansson 2002, Jorgensen et al. 2006, Hallstedt 2008, Deutz et al. 2010). Third, to combine widely used initiatives (e.g. life cycle assessment, ecodesign, cleaner production and corporate social responsibility) to support corporations in their sustainability efforts (Lozano 2012). Fourth, to emphasize the importance of effective communication (Pujari et al. 2004).

1.1 Strategic Sustainability in Product Development

To be able to efficiently and strategically work towards sustainability, it is important to define and agree on what sustainability means for the company (Broman et al. 2000) to ensure that a complete sustainability perspective, including both ecological sustainability and social sustainability, is used to guide innovation processes rather than single aspects of sustainability. Strategic sustainability aims for a well-defined sustainable situation and gives guidance for how work towards it in a strategic step-wise approach. It is used in this paper to indicate a difference between strategic sustainable product development and ecodesign, which essentially strive to do improvements in environmental impacts.

A Framework for Strategic Sustainable Development (FSSD) has been developed with the aim to clarify, on an overall level, what is required for the social and ecological systems to be sustained. This differs from corporate social responsibility (CSR), “triple bottom line” (Elkington 1997), etc., which focus on sustaining a corporation; these concepts describe different systems that are to be sustained. In essence, sustaining a business is much different than sustaining society, and these cannot be put on the same operational level, a point that Dyllick and Hockerts (2002) conclude with. However, the CSR concept has evolved to emphasize the stakeholder involvement and responsible behavior from corporations and could on an operational level be of value as a complement to the FSSD. The FSSD also specifies a generally applicable definition of sustainability expressed as first-order principles (Holmberg and Robèrt 2000; Ny et al. 2006; Missimer et al. 2010). In essence, these first-order principles act as a root cause analysis for social and ecological issues. This differs from many other approaches, which tend towards reducing symptoms of society’s unsustainability, e.g. minimization of resource usage, source reduction, dematerialization, etc. See Glavic and Lukman (2007) for a discussion of related terms, and Johnston et al. (2007) for discussion of the benefits of a concrete definition of sustainability such as the one used here. This root cause analysis encourages open-ended and non-prescriptive co-creation towards sustainable solutions that do not miss or give preference to certain sustainability aspects. The FSSD has been used and implemented by senior managers in different types of businesses to guide strategic decisions with a sustainability component (Robèrt et al. 1997; Anderson 1998; Leadbitter 2002; Matsushita 2002; Nattrass and Altomare 2002).

Robèrt (2000) explains the need for such a framework, and elaborates how some other tools and concepts commonly used in the domain of sustainable product development relate to it. The use of the FSSD is supported by others who have described the benefits of using the FSSD model to provide support to planning efforts. For example, Korhonen (2004) identifies four risks for industrial ecology outside of the FSSD model and MacDonald (2005) presents the benefits of using the FSSD to support the optimization of the use of ISO 14001 as an environmental management system. Baumgartner and Korhonen (2010) pick up on this in an editorial article that introduces Wikström (2010). Wiktröm delves into three different approaches organizations take when pursuing sustainability initiatives. These research results essentially support Robèrt's emphasis on the need to clarify which system it is to be sustained: the organization, or the organization within the context of the global social-ecological system?

To go beyond methods and tools development it is also important to consider: i) how a decision system, including data and actors involved at different organizational levels and at all levels of a company, could integrate sustainability aspects (Dangelico and Pujari 2010, Hallstedt et al. 2010, Labuschagne et al. 2005); ii) how knowledge of sustainability aspects can drive product innovation processes (Sherwin and Bhamra 1999, Thompson 2010); iii) how to develop sustainable product-service systems (Manzini and Vezzoli 2003, Martinez et al. 2010); iv) introducing a framework for sustainable consumption and production (Tukker et al., 2008), and v) develop and use business models that support sustainable innovation (Boons and Lüdeke-Freund 2012). Predictions of consumers' future desires and the company's capabilities of meeting these are critical for success. The rapidly increasing significance of sustainability on the market adds aspects to consider and puts special demands on the integration of a socio-ecological sustainability perspective in the product development companies. The paradigm of product development towards increasing value (and profit) by reducing costs and increasing benefits is unlikely to change. However, where and how sustainability aspects are brought into the product development process is possible to change, to support both the reduction of costs and the increase of benefits (Waage et al. 2007; Schmidt and Taylor 2006).

1.2 Purpose of Study

The aim of this research is to present key elements for successful implementation of a strategic sustainability perspective in product development. The key elements have been derived based on an extensive exploratory and mainly descriptive study with a qualitative research approach. An in-depth interview study has been undertaken together with a review of literature, previous research results and company documentations to evaluate if and how strategic sustainability has been successfully implemented in the day-to-day basis in the product innovation processes of the studied companies.

In contrast to theoretical studies and research on how sustainability can be integrated in product development, this study contributes to a picture of the state of practice for sustainability implementation and adds value to recommendations and findings about sustainability integration from previous research.

2 Research Methodology

2.1 Conceptual Frameworks

This article uses a conceptual understanding of sustainability that is based on the framework for strategic sustainable development (FSSD), briefly presented above and described more in-depth in section 2.1.1. A model of the product innovation process has been developed based on Roozenburg and Eekel's (1995) model of the product innovation process and adapted with insight from Sarkis's model of the product life cycle (Sarkis 2003). This adapted model is introduced in 2.1.2.

2.1.1 Strategic Sustainable Development

The FSSD used here is based on the concept of backcasting from basic socio-ecological sustainability principles (Robèrt et al. 2002). The FSSD consists of five interdependent but distinct levels that are explored to establish their respective contents and relationships for the particular planning case. The five levels of the framework encourage a thorough enough understanding of the system (1) to be able to arrive at a robust principled definition of the goals of the planning exercise (2), which is a prerequisite to be able to be strategic (3) with regard to prioritizing actions (4) and selecting tools (5) for e.g., monitoring, coordinating and decision-making.

Three aspects of the FSSD together make it unique:

i) First, the clarification that it is society within the ecological system (level 1 above) that is ultimately to be sustained, i.e. not a specific product, organization, nor the economy. The authors are not aware of any other framework or approach that clarifies the system to be sustained as the socio-and ecological system. This differs from many early sustainable development-related concepts that have primarily environmental connotations (e.g. life cycle assessment). It is also different than concepts that consider ecological, social, and economic systems to be on equal levels (e.g. "triple bottom line"), which confound solutions (Johnston et al. 2007). The FSSD is also different from corporate sustainability efforts that seek to utilize sustainability for the benefit of individual organizations, partly in that the FSSD maintains a focus on only what is necessary for the sustainability of society, and not an individual organization (though proposes to support those organizations that utilize the perspective the FSSD provides).

ii) Second, a first-order principle definition of sustainability (level 2 above) that describes boundary conditions within which a sustainable society will operate. These principles claim to be scientific, necessary, sufficient, concrete and non-overlapping (Ny et al. 2006) in order to simplify complex processes without being reductionist (Broman et al. 2000). Others argue that they are not designed for the socio-economic complexity in the world (Upham 2000). The sustainability definition for the social system is less robust, and currently under development (Missimer et al. 2010). Some emphasize that sustainability is dynamic (Hjorth and

Bagheri 2006; Lozano 2008) or "a moving target" (Gaziulusoy et al. 2012); while some others emphasize a precautionary approach (e.g. Cooney 2004; van den Belt 2003; Manson 2002). The FSSD definition is intended to be both precautionary and constant, preventing systematic degradation of the socio-ecological systems with a definition that does not change over time.

iii) Third, the use of backcasting to be strategic (level 3 above). In short, backcasting means imagining success in the future and then looking back to today to assess the present situation through the lens of this success definition and to explore ways to reach that success (Robinson 1990; Dreborg 1996; Vergragt and Quist 2011, Quist et al. 2011). Backcasting gives support in being strategic in the development towards sustainability (Gaziulusoy et al. 2012), in part because it enables moving in the right direction via "flexible platforms" in order not to move into "blind alleys" that might prevent continued progress (Ny et al. 2006). A variety of approaches to backcasting exist, and they can, though do not necessarily, lead to potential for system innovations (Quist et al. 2011).

Time can also be considered a dimension of sustainability as indicated by Brundtland (1987) and discussed by Lozano (2008). The FSSD addressees time through the concept of backcasting from the future, which implies a need to think about transition pathways from the present. Also, the success definition of the FSSD lies outside the bounds of time, i.e. the sustainability principles are intended to be applicable now and in the future.

There may be some limitations to the use of the FSSD. Neither does it directly and easily integrate into the product innovation process; i.e. the FSSD is not a tool that can simply be embedded into existing decision systems. Nor does it give explicit guidance with respect to economic dimensions (Lozano, 2012). Therefore, previous research suggests to inform other tools or integrate other tools, that product developers use, with FSSD e.g. Robert et al. (2002); Byggeth et al. (2007); Ny et al. (2006); Thompson et al. (2012). Also, on-going research aims to link FSSD-based sustainability assessments and support tools with company- and customer values to guide decisions more efficiently.

2.1.2 Product Innovation Process

Roozenburg and Eekels' (1995) model of the product innovation process was used as a base in this study, and was modified with ideas drawn from Sarkis (2003) and the authors' own experiences from product development. According to Roozenburg and Eekel's model, the product innovation includes both "product development" and "realization", i.e. both developing the product and getting it into use. The majority of sustainability-related impacts happen due to the realization of the product, e.g., in the extended product life cycle. However, sustainability aspects need to be integrated into the process when the product is being developed because that is when it is possible to influence aspects of how the product will be realized. Roozenburg and Eekel's model shows the connection between "product development" and "realization," and the modified version presented in Figure 1 further emphasizes this connection together with a more explicit representation of the product life cycle as presented by Sarkis.

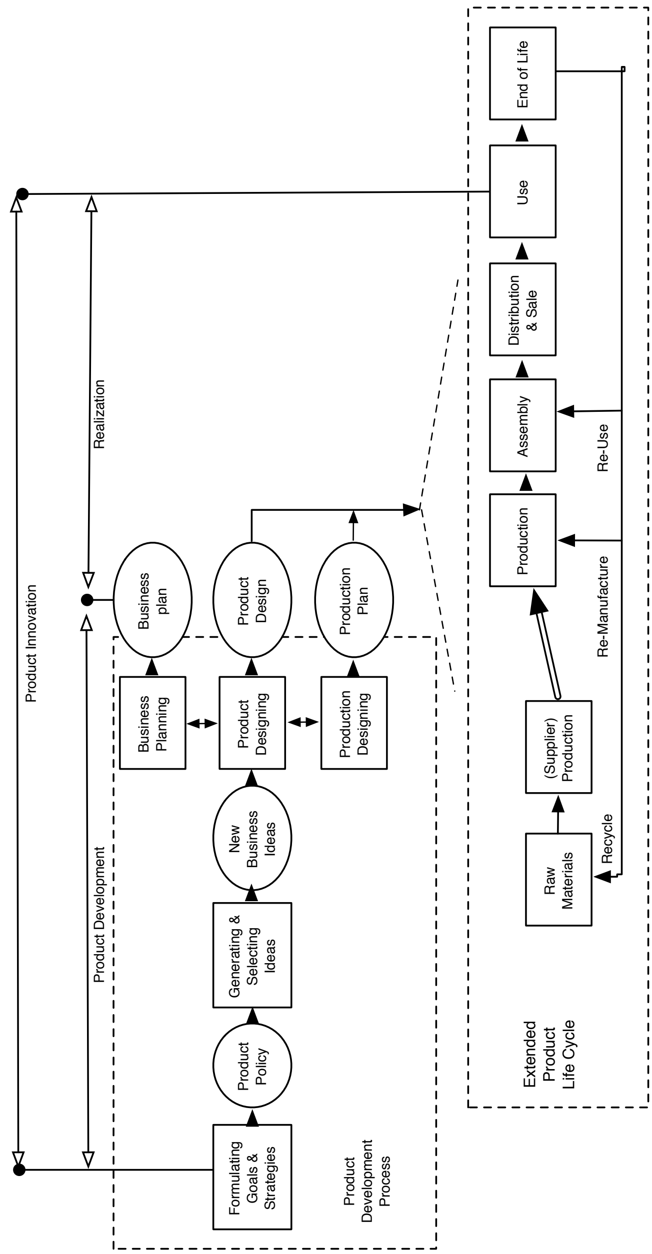

Figure 1. The Product Innovation Process with Product Life Cycle (adapted from Roozenburg and Eekels (1995) and Sarkis (2003)).

2.2 Methods

The research approach in this article draws inspiration from the Design Research Methodology (DRM) articulated by Blessing and Chakrabarti (2009). In this approach of designing research into the design process, a literature analysis is conducted to support clarifying research goals. Empirical data is then collected and analyzed as a descriptive study of the state of practice in the subject of study in order to arrive at an understanding of how the subject works prior to an intervention. Then, prescriptions are made to change how the subject is working by providing new methods or tools as support. Finally, a descriptive study is conducted again for comparison with the initial description and for making an evaluation of the impact of the prescribed changes.

The intent of this study was to merge a backcasting approach with the DRM approach, which can be summarized as "describe – do a change – describe – compare" according to the following:

1. Describe an envisioned product innovation process that includes a strategic sustainable development perspective, based on previous research and literature studies;
2. Describe how six companies are working with a regard to a strategic sustainable development approach in their product development processes, based on a qualitative research approach with in-depth interview studies and internal company documentations; and
3. Compare the current state with the ideal vision in order to understand what companies do in practice to fulfill the vision and to suggest changes where there are gaps between the practice and this vision.

Essentially, this process of stages, see figure 2, provides us with a more elaborate approach to arrive at what could then serve as input into a "Prescriptive Study".

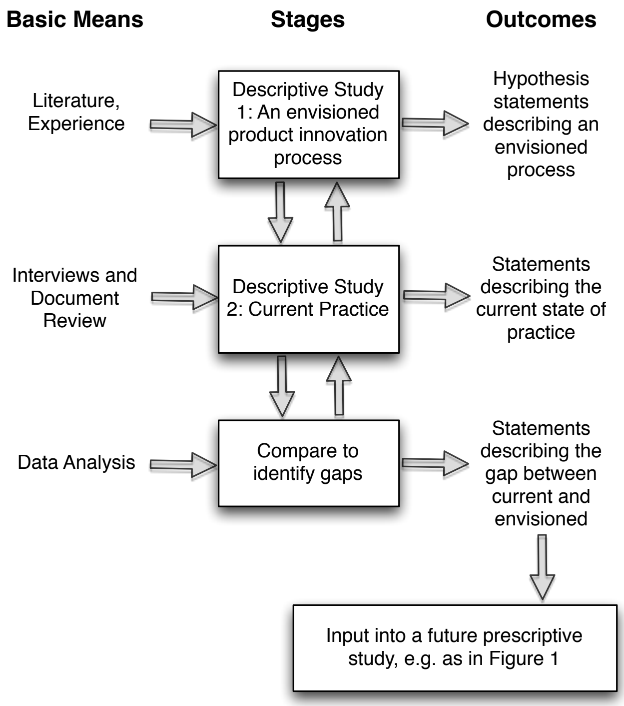

Figure 2. The research approach used.

Six large manufacturing companies (each over 1000 employees) in a Corporate Group, referred to here as A-F, were used as cases to explore and evaluate if and how strategic sustainability has been successfully implemented in the day-to-day activities in their product innovation processes. Apart from studies of the product development process documents, interviews were conducted at these six companies. The six companies are tightly integrated in that they share a common operational management system and global development process. Also, the six companies have some support tools in common, and they also share the same corporate standards and values. In other operational aspects, they are separate companies. The rationale for working with these companies belonging to the same Corporate Group was in part to identify possibilities to increase collaboration in the sustainability area by identifying some common challenges, and possible synergies for increasing the inclusion of a socio-ecological sustainability perspective in product planning and development. Further, the rationale was to learn from what these companies already do well with regard to sustainability aspects, as they are generally perceived by both themselves and their peers to be global leaders in this area. The Corporate Group was listed in the Dow Jones Sustainability World Index in 2010, which contributed to this view. This listing indicated that the Corporate Group, to which the six companies belong, was part of the ten percent highest rated companies in the world in terms of their sustainability performance. The Corporate Group was in particularly good at environmental issues, work environment, corporate governance, compliance with the Code of Conduct, and anti-corruption policy (DJSI World 2010).

According to the first stage described above "Describe an envisioned product innovation process including a strategic sustainable development perspective" we hypothesized about how companies could be working if they integrate a strategic sustainable development perspective in their product innovation process. This is elaborated in section 2.2.1.

To test these statements, we conducted interviews and reviewed documents and the companies' documented processes. The interviews were guided by a set of semi-structured interview questions. The questions were divided into five groups (see appendix A), and were intended to provide insight into the five statements listed below.

2.2.1 An Envisioned Strategic Sustainable Product Innovation Process

Drawing upon previous research results (mentioned in the introduction) and own experience facilitating workshops etc. using FSSD, an envisioned product innovation process including a strategic sustainable development perspective was described as statements. These hypothesis statements, listed below, were used to guide the interview questions (Appendix A).

1. The company will have a clear understanding of sustainability, and product requirements that have been developed with consideration of sustainability will permeate the product innovation process and be monitored by the product development team.

In essence this means that companies understand the global changes that contribute to both risks and opportunities that their profitability depends upon. Companies may or may not explicitly define success from a sustainability perspective, but it should be clear how they utilize awareness of sustainability aspects in their work.

2. There is a combination of forecasting and backcasting in the companies' decision support tools.

This is important since backcasting is critical to provide opportunities for radical innovations by breaking from existing trends, and forecasting alone may miss strategic opportunities or lead down blind alleys that are costly to recover from. At the same time, companies exist in the current reality of today, and practically must move forward from their current situation using forecasting as well.

3. The company will include competencies when taking sustainability-related decisions throughout the product innovation process.

It is important to bring in various roles with the competencies that together give a good knowledge of a product's sustainability aspects throughout its lifecycle, and communicate with other actors in the value chain, which also influence the sustainability performance.

4. Sustainability-related requirements will be considered early in the product innovation process to influence the direction of development.

This is consistent with most product development literature in the general sense: in order to influence the life cycle performance of products, knowledge needs to be available and utilized early in the process (see e.g. Ullman 1997).

5. The company will have support tools for dealing with sustainability aspects.

We did not hypothesize about which tools, nor if those tools would be considered sufficient – only that there would indeed be some tools used in the development process specifically for the sustainability aspects.

2.2.2 Interviews and Document Review

Semi-structured interviews were conducted with two to seven employees from each company (in total twenty people). The employees had an average of 12.5 years of working experience at these firms (see appendix B). Interviewees were selected to provide input from the areas of advanced engineering and product planning, project management, product development, purchasing, and environmental management and assessment.

Two or three of the authors were present for each interview, and an audio recording was made for each interview. Interview sessions were initiated by clarifying key terms. Following the interviews, each researcher summarized the results from the interview based on his/her own notes, with access to the audio recording. All of the researchers' summaries were then compiled to arrive at one set of notes for each interview. The interview results were sent back to the interviewees for an opportunity to confirm (or correct) the result.

In addition to the interviews, steering and product policy documents, support tools and working processes were studied to get a better understanding of if and how a socio-ecological sustainability perspective is integrated in the documented product innovation process today.

3 Results from Interviews and Document Review

The results from the interviews and the document review are divided into four parts, based on the tested hypothesis statements described in section 2.2.2. The four parts are: i) overarching strengths for implementing a strategic sustainability perspective in the product innovation process for the investigated companies; ii) challenges identified for "making the right products" ("product planning" in Figure 1.); iii) "making products in the right way" ("strict development" in Figure 1.); and iv) challenges regarding methods and tools.

The results show that there are some shared strengths and challenges on an overall level and there are specific common challenges related to processes and tools.

3.1 Common Strengths

The Corporate Group has a large influence

The interviews clearly showed that a significant reason why the six companies had substantial support for implementing a strategic sustainability perspective in the product innovation process was thanks to corporate standards and steering documents, such as an environmental policy and internal requirements for environmental and social considerations. The shared mission and vision (the Corporate Group and the individual companies) were also important elements for laying the groundwork for formulating goals and strategies and for providing high-level guidance for future products. The Corporate Group strives for being strategically ahead of competitors and legislation ("strategically ahead" means being among the leaders, but not being so far in front that it hurts profitability). This also means that all the companies that were involved in the survey did perceive that they were ahead of both competitors and regulations.

> *If we talk about sustainability and production… the toughest demands come from our owners, the Corporate Group, and also from authorities, and considering both environmental issues and working environment issues. It is a matter of survival…we have to be good at environmental issues.*
> (Environmental Manager in Company B)

Common support tools, cooperation and knowledge from previous assessments

Another strength within this group of companies is that they work with similar product innovation processes and therefore can more easily share support tools and cooperate within projects. The current level of cooperation appeared to vary; frequently two or three of the companies would work jointly on projects and occasionally all six of the companies would work together. The strength appears to lie as much in the potential to benefit from the shared processes as in cooperating in common projects.

All six companies have implemented an Environmental Management System (ISO 14001) and use routines and support tools for including sustainability aspects in their product innovation process. The specifics of this are elaborated in the next two sections, but it is mentioned now as the fact that all of the six companies have some type of routines and tools to include sustainability aspects constitutes a common strength.

Another strength is that each of these companies is already doing some type of environmental impact assessment (EIA) or life cycle assessment (LCA) on their products. This is a strength because it means that the companies i) have at least a minimal capacity to conduct these assessments, and ii) already have results from previously conducted EIAs or LCAs. These prior assessments can therefore provide learning to the project groups that can be applied in future projects. While having these assessments is a shared strength, there was, however, no evidence that there was a systematic way of incorporating that knowledge into future projects.

3.2 Common Challenges Regarding "Making the Right Products"

Incorporating backcasting together with forecasting

Forecasting (i.e. analyzing and projecting trends) currently dominates product planning in the studied companies. Backcasting (i.e. looking back from an imagined point in the future in order to explore strategies to get there) was not used for planning strategically to implement a sustainability perspective in the product innovation processes. The potential improvement is to open up the idea space using backcasting from overarching principles for success. In the context of product development it could stimulate and generate new and/or innovative solutions. This could be a potential improvement, since backcasting together with forecasting could provide a longer-term context within which to make shorter-term (tactical) decisions that align with longer-term strategy, and thus better support moving towards more sustainability-driven product innovation.

Sustainability is not included at a high level in advanced engineering

One challenge concerned the placing of responsibility for having a sustainability focus during advanced engineering, when new product concepts were being explored and evaluated. Currently there is a very strong focus on the technical aspects and business opportunities of product concepts being explored, but very little consideration of the sustainability implications of these product concepts. A potential solution frequently suggested by interviewees to address this challenge is to create a new role to focus specifically on sustainability aspects in advanced engineering. This role could make sure that the "right questions" with regard to sustainability aspects are asked when talking to product developers, buyers/procurers and customers and that the sustainability aspects and their relation to the business value are explained and systematically included in the product requirements list. By having a specialist at each company that has the overview of sustainability aspects and market knowledge with the purpose to represent the customers' interests in all the projects and who, at the same time, could answer the question: "What makes us to be in the forefront?", a strategic next step could be planned for. The Advanced Engineering group, or an equivalent group, has this role to some extent, but they primarily focus on detailed technical questions. Someone with a similar function for the sustainability area is needed.

> …*many times the requirement list does not include the environmental requirements as nobody is fighting for those as much as the other requirements.*
> (Product Developer in Company C)

Win-win-win situations for people, planet, profit

A significant challenge for taking sustainability aspects into account in product development is to know what the customers are willing to pay for. This means that it is important to find the balance between the added value through reduced environmental impact and the extra cost that reduction often entails. The challenge is to find a win-win-win situation and to identify situations where sustainable improvements are aligned with business advantages.

> *Most of the customers do have a short term perspective and look at what we have today and what can be done better on a technical level. About 80-90% of customers want a product with as little environmental impacts as possible. However, they cannot afford to spend extra money on it.*
> (Environmental Manager in company A)

Related to the win-win-win concept, being able to "make the right products" requires the broader societal systems being prepared for these products. The companies feel restrained with how far they are able to "be out in front" because their products rely on infrastructure that is outside of their direct control.

> *We can make [our product]… what energy source does society want? And is there the infrastructure to support it?* (Design Engineer from Company D)

3.3 Common Challenges Regarding "Making Products in the Right Way"

Missing a complete consideration of social sustainability across the full product life cycle

With regard to social sustainability, working conditions at suppliers are considered during supplier assessments, both with regard to choosing new suppliers and in reviews of current suppliers. Good working conditions for the companies' employees, including production staff, were emphasized, including things like physical safety, low noise, and very low proximity to toxic substances. Social aspects are also considered to some extent, for example in the usage phase, but not typically in the end-of life phase. Overall, social sustainability was less a "top of mind" issue than was environmental sustainability, likely because "environmental care" is one of the core values for the corporate group.

No systematic learning from environmental impact –and life cycle assessments to future projects

A more systematic use of the environmental assessments is needed to increase use of the knowledge about the environmental consequences from product components and their related processes that is created during these environmental assessments. A systematic way to collect and access data is needed. Modifying existing processes in order to use information/evaluations again could also increase the efficiency in future development projects.

More involvement of procurement staff

Purchasers/buyers, with their extensive knowledge of suppliers' products and facilities, could be more actively involved earlier in the innovation process as they have knowledge about material contents and manufacturing processes for certain materials. Purchasers/buyers build relationships with suppliers, which in turn provide them with key insights regarding sustainability aspects at those suppliers, e.g., social aspects like working conditions in the factories, or environmental aspects of their production processes. The purchasers/buyers have significant knowledge about the different manufacturing processes of suppliers and could give input in the early phases such as guidance to preferred suppliers and their manufacturing processes.

Some interviewees expressed a desire to consider procurement earlier in the concept- and product- development phases based on the idea that procurement has an important contribution to make with regard to sustainability issues.

> *We should be involved in the product concept phase. One of the first times I was involved so early in the process was when an Environmental Impact Assessment was conducted. In the future, the suppliers too need to be much more involved in the process.* (Purchaser/Buyer in company B)

Generally, the results showed that the communication between product developers and suppliers could be more efficient. The designers could for example inform the purchasers better through ear-marking certain product parts to specify how some parts need to be specifically treated due to environmental issues. This more proactive approach, with a sustainable development perspective, could avoid a late discovery of issues, e.g. manufacturing processes with high socio-ecological impact, and thereby avoidance of an extra development cost.

3.4 Common Challenges Regarding Methods and Tools

Results from EIA/LCA necessarily come late in the process, preventing major changes to the product

Decisions regarding major sustainability implications are made mainly in the concept phase of the product innovation process. A common environmental impact assessment (EIA) is intended to be used to guide decisions in a current project, but practically the guidance from an EIA often comes too late to really provide significant guidance in the current project. This is because the nature of an EIA, similar to a life cycle assessment (LCA), requires that many decisions regarding a product concept already are made in order to be finalized. Also, the EIA/LCA tools are not applicable for solution seeking. Their usefulness is bound to be "reactive" from a development perspective.

> *If it takes too long to get an answer from an assessment, then you've already ruled things out and you don't even evaluate those concepts.*
> (Environmental Coordinator in Company E.)

In the companies, LCAs are mostly done on new products or new concepts and are important in two aspects: i) Learning for future projects comes from LCA results, especially with regard to end-of-life aspects of materials, and, ii) often LCA results must or could be delivered to customers.

> *The LCA has not had a direct affect on the current products, but it has given an understanding and increased knowledge. Since we have done LCAs, which probably none of our competitors have done on that level, we have always had good overview of the materials we use.*
> (Environmental Manager in company A)

Tools for material selection do not consider scarcity, social impacts and recyclability

Interviews indicated that a support tool for material selection that includes information to anticipate which materials would be allowed from a sustainability perspective with both short-and long-time perspective is requested. Material availability/scarcity is in the minds of product developers, but there is not really a good way to consider it. There is also a need for a tool in product development for material selection in the long-term perspective that considers scarcity, resource availability, and material recyclability/reusability, especially with regards to those scarce or limited materials that will affect costs and legislation. Such a tool is lacking at the moment and would be helpful in the product development team.

Simulation of sustainability consequences across the product's life cycle

There is a desire for a support tool that could guide the choices of a product life cycle and visualize the consequences of different choices throughout the life cycle. The usefulness of such a tool could be a system analysis on the full product life and simulation of the sustainability consequences for how and what to optimize. Simulation capability of sustainability consequences on the full product life is probably necessary to quantify and assess (at least qualitatively) the socio-ecological characteristics of a concept. The information about sustainability consequences could then be used to compare with other design properties, which are simulated to give a decision base, such as stresses and performance parameters.

4 Discussion: Key Elements for a Strategic Sustainability Perspective

Overall, the results indicate that one of the most crucial changes needed for an implementation of a strategic sustainable perspective is to open up the idea space using backcasting from overarching principles for success. Backcasting from principles together with forecasting could provide a longer-term context within which to make shorter-term (tactical) decisions that align with longer-term strategy, and thus better support moving towards more sustainability-driven product innovation.

Based on the results from the investigation and previous research, eight key elements for successful implementation of a strategic sustainability perspective in product development are suggested. These key elements are divided into four categories: organization, processes, roles and tools. The Organization category refers to elements that are relevant to the entire company. The organization has Processes that it follows in order to do its work. Within those processes, there are Roles that suggest who should be involved. Tools can be used by people in those roles at various locations within the process. Roles and Tools are listed before Processes so that appropriate places in the process can be suggested.

4.1 Organization Level

Key element 1: Ensure commitment from senior managers through a strategic sustainability plan that is well communicated at the company, as there is a complexity in many dimensions.

The study showed that one of the common company strengths is that each company has a clear commitment to sustainability in their mission and vision. Additionally, the Corporate Group has an environmental policy that lists "care for the environment" as one of three core values. This high-level commitment to sustainability aspects is an important element, because it lays the ground for formulating goals and strategies for guiding what the next products will be. The result from our survey gives an indication that sustainability is a priority area on a higher management level in the Corporate Group. This was also confirmed by one of the interviewees:

> *I am proud to work for our [Corporate Group]. The CEO has really prioritized environmental issues. We will sell products because we are a good citizen in society. Our customers notice that, and our owners and investors see this and we will get more money for it. We don't do anything except earning money – that's our main goal, and it will always be like that. But you can do it in different ways, and this is a very good way to do it. To be a good citizen.*
> (Buyer/Purchaser in company B)

In addition to management commitment, it is relevant to have a strategic sustainability plan that is well communicated at each company, as there is a complexity with many aspects and areas dependent of and connected to each other. Otherwise, there is a risk of focusing on one issue at a time, not seeing the overall picture. The importance of a well-communicated strategic sustainability plan is also stated by Pujari et al. (2004).

The current focus at many companies is to reduce the emissions and fuel burn, and less emissions means less weight means design changes. But the next issue might be scarce material – and could be unforeseen by companies focusing only on current factors – which also might force new design solutions. Product developing companies are encouraged to extend their system analysis beyond only the product, to include the complete product life.

4.2 Process Level

Key element 2: Efficiently bring in a sustainability perspective early in the product innovation process and align them throughout the design process, in order to take these aspects into account and consider sustainability-based criteria with the same importance as any other criteria in the product development process.

One of our suggested key elements of implementing a strategic sustainability perspective in the product innovation process is to have a process to identify the key sustainability criteria for the different product components. The reason is to consider these sustainability criteria with the same importance as any other criteria in the product development process. Company A had reached furthest with this and had also identified some environmental criteria on an overall level to include already in the product planning phase for all the company's product innovation projects. These criteria were then broken down to product requirements and taken into consideration with the same importance as any other requirement in the product development. Our suggested improvement potential for the Corporate Group is to define a generic methodology for how to identify these sustainability criteria to ensure that no important sustainability aspect is neglected.

If the identification of these sustainability aspects would come into the product requirement list, we argue that it would be easier to i) reduce the environmental impact and avoid costs, ii) plan for solutions as flexible platforms towards a sustainable solution, and iii) use sustainability as drivers for product-service system innovations. The importance of defining sustainability criteria and consider these as equal partners to the traditional requirements of cost and quality from the very beginning for successful implementation are also emphasized in Waage (2007), Kaebernick et al. (2003) and Pujari et al. (2004).

> *Success is unlikely to follow from an attempt to integrate environmental issues late in the product development process...*
> *(Pujari et al. 2004)*

Key element 3: More actively bring in procurers/buyers early in the product development process, as procurement has an important contribution to make with regard to sustainability issues.

With regard to process changes, we suggest that procurement staff/buyers should be involved earlier in the concept- and product- development phases as they have the primary contact with suppliers and therefore knowledge about emissions and manufacturing processes for certain materials. This suggestion is based on the result from the interviewees as they expressed a desire to consider procurement earlier in the product innovation process since procurement has an important role for bringing in sustainability issues. The relationships that people working with procurement have with suppliers often provide them with key insights regarding sustainability aspects of those suppliers' processes.

Other studies have shown that the involvement of suppliers directly in the early phases is beneficial and could result in a more efficient product development, including reduced development costs, higher quality, and reduced time to market as well as contributions to new innovations (Petersen et al. 2005; Huang and Mak 2000). Previous research has also shown that a high degree of supplier involvement in the product innovation process has a positive effect on the product's environmental performance (Pujari et al. 2004). Guidance for how to select suppliers and a methodology for enabling better supplier involvement, as well as a mechanism for facilitating information sharing between the customer and suppliers, are proposed in a web-based framework called Wibid by Huang and Mak (2000). These or similar support tools could be relevant to use in order to increase supplier involvement in the early phases of the process.

Key element 4: Include social aspects across the product life cycle and its value chain, as it affects the long-term company reputation and image, investment plans, quality control and efficiency.

We state that there is also a need to bring in the social sustainability aspects (e.g., protection of internationally proclaimed human rights, no toleration of any form of forced, compulsory or child labor, etc.) across the product life cycle and its value chain. This needs to be done because product solutions need to be supported on a market for a significant period of time and dependencies on unsustainable suppliers come with a significant risk as this affects the long-term company reputation and image, investment plans, quality control and efficiency. In the survey it was found that necessary supplier assessments were done on a regular basis, where one large and mandatory assessment emphasizes the social sustainability aspects. To involve and assess suppliers in this way, which is what the companies in the survey do, is excellent from a risk perspective and also supported by others (e.g. Petersen et al. 2005). The improvement potential for the company group not only includes social sustainability in the supplier assessment and to some extent the usage phase, but also includes social sustainability in the end-of life/recycling phase.

To take a full sustainability perspective means to include both an ecological and social sustainability perspective, which affects the economical sustainability dimension. These perspectives are sometimes separated, as social sustainability has been harder to define and quantify compared to ecological impacts. However, recent work with guidance on social responsibility by the International Standard Organization (SS-ISO 26000:2010) and UNEP's suggested guidelines for social life-cycle assessment of products (Benoît and Mazijn 2009) as well as research, e.g. Missimer et al. (2010) and Rothstein (2000a, 2000b), have taken this a step further. The integration of a full socio-ecological sustainability perspective in processes (Bratt et al. 2011), tools (Byggeth & Hochschorner 2006), or assessments (Hallstedt et al. 2010) still constitutes a challenge and needs further development and research.

4.3 Roles/People

Key element 5: Identify the different levels of roles for people responsibility for sustainability implementation in the product innovation process.

One of the improvement steps for some of the companies, and suggested as one of the key elements for a successful implementation, is to have someone with the role and responsibility for sustainability implementation in the product innovation process. This person should be able to give answers concerning the next strategic step for integrating a sustainability perspective in product development and also give answers to the question "What puts us in the forefront regarding sustainability?" Most of the companies did have persons/roles, for example an environmental coordinator, environmental council leader and/or advanced engineering person, responsible for answering this type of question, which can result in a faster and more efficient implementation of sustainability in the product innovation process, than if no one is responsible for this question. Still, there were some improvement potentials in some of the companies where the responsible role for integrating sustainability in product development and product innovation process was not always clear. Instead this responsibility was often added to all the different tasks for the environmental manager, who had difficulties getting involved in product development projects and who was not part of the product development team.

We suggest that each company at a minimum level needs to identify the different roles of responsibility for sustainability implementation in the product innovation process, as it was shown that sustainability aspects otherwise was added late in the product innovation process (if at all), preventing them from being used as a driver towards more innovative solutions. In addition to our suggestion, Pujari (2006) states that in the future there is a need for a closer integration of the work of product development managers, marketing managers and environmental managers and a higher degree of cross functional co-ordination. He also emphasizes the need for a more integrated role for the environmental coordinator to provide environmental guidelines to product development teams and contributing in the implementation process, as well as conducting environmental assessment at every stage gate of the product innovation process. This means that a proactive company needs to identify the roles and responsibilities as well as coordination between different teams for successful sustainability implementation in the product innovation process.

4.4 Tools

Key element 6: Introduce a systematic way for competence building, including knowledge sharing follow-up actions and, re-use of evaluations in order to increase the competence in the sustainability field and by re-using experience efficiency will be increased.

During several of the interviews, interviewees explained that life cycle assessments (LCAs) or environmental impact assessments (EIAs) had been completed in order to comply with legislation or customer demands. An extensive data collection exercise was undertaken for those assessments, and significant expense was incurred to bring the data together and perform impact assessments. Much knowledge and experience were gained in this process. The design and production process typically remained unchanged, however, primarily because the design was already set and approved. Interviewees suggested that there was an intent to use the knowledge and experience that had been gained for future development projects. However, when asked about how exactly this knowledge and experience would be used, the interviewees could not verify a process or identify tools or methods that would ensure the capture and re-use of that knowledge.

There is an opportunity to utilize knowledge sharing tools in the studied companies in order to both increase the sustainability aspects of products, as well as to reduce design costs. For example, experience regarding certain processes or materials already assessed from a sustainability perspective could guide decisions in future projects. Research on knowledge-based engineering and on how to efficiently re-use experience (Andersson et al. 2011) conclude that there are several phases in a life-cycle of experience such as: identify; capture; analyze; store; search and retrieve; use and re-use experience and knowledge. We argue that it is relevant to use support tools for how to most efficiently capture, store, search and retrieve knowledge as well as re-use it in future projects for successful sustainability implementation. To build up a system for how to re-use knowledge in the sustainability field could then be part of a technology platform.

Key element 7: Include tools for guiding decisions as a complement to assessment tools, as it could provide additional decision support for longer-term strategic decisions on a short-term perspective towards a more sustainability-driven product innovation.

The tools and methods used at the companies for integrating sustainability aspects in the product development phase are primarily used for evaluation and assessment. This means that there is a significant opportunity to more proactively guide the product developers in finding new solutions and ideas for sustainable innovations as well as providing guidance for more sustainable production processes.

It is important to have the product impacts through the full life cycle mapped out in order to see the challenges that need to be solved and make improvements according to this. However, stronger support for the product developers is suggested in the terms of guidance from a strategic sustainability perspective. Support tools such as a Method for Sustainable Product Development (Byggeth et al. 2007) and Templates for Sustainable Product Development (Ny et al. 2008) with this purpose have been developed through research and could be adapted to the processes and tools used at the companies. These tools are based on a backcasting approach and could be a good complement to the forecasting approach used today at the companies, thereby providing additional decision support for longer-term strategic decisions on a short-term perspective towards a more sustainability-driven product innovation.

Key element 8: Use tools that incorporate a backcasting perspective from a definition of success, to develop products that could function as flexible platforms towards more sustainable products and at the same time generate good return on investments.

In order to reach a sustainable society sooner it is necessary to make more radical innovations and more leap-frog solutions (Baumgartner 2011; Baumgartner and Korhonen 2010). However, based on the interviews at the companies it is clear that it is hard to make decisions regarding sustainability issues leading to more radical changes because a whole network of companies have to move in the same direction simultaneously. Many companies are dependent on others in the value chain, for example those companies that develop components that are only a part of the complete product system. This makes a change towards radical innovations a slow process. To collaborate with the stakeholders (suppliers, customers, the Corporate Group) and the whole value chain (suppliers, customers, end-of-life stakeholders) is essential and is already natural for some of the companies in the survey. A slow change is also due to decisions taken in the product development process which will have an impact for maybe 30 years as some of the products typically are in operation for 40-50 years. It is important to be aware of this time delay, and for this reason make decisions based on backcasting from success principles for a sustainable product together with predictions of the sustainability consequences that will present themselves. This is consistent with the findings of Quist et al. (2011) regarding the impact of backcasting and Gaziulusoy et al. (2012) on the benefits of a scenario method to aid companies in aligning innovation efforts with short-, medium-, and long-term requirements.

At the company group, innovations related to sustainability are mainly driven by customer and market demand, stricter legislation or the internal requirements from the Corporate Group. These types of innovations are possible if they are related to; i) reduced cost and/or new business advantages, ii) improved image for the customer and the companies, and/or iii) approaching legislations. We therefore recommend companies to explore the estimated costs for sustainability consequences of different solutions over time and include this in the early phases in the product innovation process. It could also be valuable to use business models to support sustainable innovations as emphasized by Boons and Lüdeke-Freund (2012).

5 Conclusion

This study offers insight to decision-makers seeking to manage product development in a more sustainable way, by exploring how product-developing companies can introduce a strategic sustainability perspective in their product innovation process. Further, it elaborates upon an intermediate level between sustainability on a corporate level and sustainable product innovation at a design level. By identifying eight key elements, this study contributes with understanding into what is beneficial at each of four categories: organization, internal processes, roles, and tools. These eight key elements are: 1) ensure organizational support from senior management; 2) efficiently bring in a sustainability perspective early in the product innovation processes; 3) utilize knowledge and experience of procurement staff in the earliest phases of the process; 4) include social aspects across the product life cycle and its value chain; 5) assign responsibility for sustainability implementation in the product innovation process; 6) have a systematic way for knowledge sharing and competence building in the sustainability field to inform decisions taken in future product development projects; 7) utilize tools for guiding decisions as a complement for assessment tools; and, 8) utilize tools that incorporate a backcasting perspective from a definition of success. Furthermore, it is critical that each of these key elements are aligned with the company's goals.

Some of the key elements could be considered as evolutionary changes and low hanging fruit, even though important for a successful implementation of a strategic sustainability perspective. While some are considered as revolutionary such as "efficiently bring in a sustainability perspective early in the product innovation processes", and, "utilize tools that incorporate a backcasting perspective from a definition of success" which will be focus in continued research. Further research on how to link the goal to become a sustainable corporation within a sustainable society could be of interest. There is also a need for continued research into how to best implement each of the key elements in an organization.

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Appendix A: Interview Questions

A. Overarching

What does sustainability mean for your company?
Do you think this will change in the coming 20 years?
What are your driving forces regarding sustainability?
What are the key market demands?
How do customers influence the early stages of the innovation process (e.g., product policy, new ideas, as well as product design)?
What does your product policy say?
Are there any sustainability components in the product policy?
Who is responsible for sustainability components in the product policy?
Is there a full life-cycle perspective in the product policy?

B. Processes

Do your company's processes (both documented and actual) match the Roozenburg and Eekel's diagram at the end of these questions? If not, how are they different?
Where and how are sustainability considerations currently taken into account in those processes?
How are design requirement lists set and who is involved in the process?
How are sustainability aspects included in the requirement list and by whom?
How do you identify these sustainability requirements?
How are customer demands incorporated in the requirement list?
How are requirements in the product requirements list verified and followed up?
How are material-related questions considered during the product innovation process?

C. Decisions

What sustainability-related decisions are taken during the product innovation process?
Who takes sustainability-related decisions?
What guides those decisions?
How do you evaluate different options?

D. Tools

What sustainability-related tools are used during product development?
For what purpose do you use them?
Who decided those tools should be used?
Are you using modeling or simulation tools to understand your product life cycle?
If yes, what aspects of a product's life cycle are modeled?
Where in the innovation process are they modeled?
If your business were shifted to a stronger Product-Service System focus, how would needs for modeling / simulation change? Are there new things that would be helpful to have modeled, e.g., user interaction with the product?

How are sustainability criteria considered in procurement?

E. Suggestions for improvement

What are the main challenges for taking sustainability aspects into account in product development?
Do you have suggestions for how to better implement sustainability perspectives in product development?
Where is there currently a need for tools? Where – if these additional sustainability considerations are added – would tools be needed?

Appendix B: Interviewees at the Six Companies

Company ID	Title	Years at Company
A	Environmental Manager	7- 15 years (average of 10.5 years)
	Feature Leader for Environment and Fire Safety	
	Purchasing Director, Supplier & Quality Development	
	Global Environmental Coordinator / Quality Systems	
B	Senior Design Leader	10-20 years (average of 15 years)
	Environmental Manager	
	Supplier Development & Environment	
	Project Manager	
C	Environmental Engineer	6-10 years (average of 8.5 years)
	Product Developer	
	Supplier Development Engineer	
D	Process Quality Coordinator	1-8 years (average of 3.5 years)
	Design Engineer	
	Advanced Engineering Coordinator	
E	Logistics Developer	2-20 years (average of 8.5 years)
	Customer Relations Manager	
	Core Values Coordinator / Environmental Coordinator	
	Purchasing Manager	
F	Technical Project Leader	5-8 years (average of 6.5 years)
	Environmental Manager	

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Paper C

Towards Sustainability-driven Innovation through Product-Service Systems

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Towards Sustainability-driven Innovation through Product-Service Systems

Anthony W. Thompson
Tobias C. Larsson
Göran Broman

Abstract

Many current sustainability considerations in industry constrain design space by emphasizing reduced material and energy flows across product life cycles. However, there are also opportunities for sustainability awareness to extend design space and drive innovation. Product-service systems (PSS) in particular can be a vehicle through which sustainability-driven innovation occurs. A framework for strategic sustainable development, including a backcasting approach, provides the basis for understanding sustainability in this work and provides insight into how incremental and radical approaches could be aligned within product innovation. This work explores how sustainability considerations can be better integrated into existing product innovation working environments, with an emphasis on opportunities that occur as sustainability knowledge leads to innovation through a product-service system approach. It is demonstrated and ideas are discussed around how sustainability can be used to drive innovation processes through product-service systems that companies rely upon, while also supporting global society's movement towards sustainability.

Keywords

Sustainable product innovation, sustainable product development, strategic sustainable development, ecodesign, product service systems (PSS)

1 Introduction

Most people that work with product innovation – both product designers and business managers – are in the dominant paradigm that puts short-term profit forward as the primary goal. However, these people are also quickly awakening to the need to more directly include both environmental and social issues in their daily decisions (Porter and van der Linde 1995). This is happening for many reasons: customer demand, an expanding regulatory environment, global resource constraints, and perceived opportunities for cost savings to name just a few.

One reason product developers have left sustainability essentially outside of their focus is that there is general confusion in the world around the topic of sustainability (Johnston et al. 2007). There is general agreement in the scientific community that things need to change (Millennium Ecosystem Assessment 2005), and this is often discussed under the term "sustainability." This paper builds upon the foundation that has been developed over the past 20 years into a framework for strategic sustainable development (FSSD) (Holmberg and Robèrt 2000). This FSSD provides an operational definition of sustainability and initial set of strategic guidelines that can be used to provide guidance to decision-makers, e.g. people working with product innovation.

With regard to products, there are two obvious things that can be changed. First, the physical artifacts themselves can be changed, and second, the way that products are managed (including how they are used) over their life cycles can be changed. For the former, more efficiency can be pursued, e.g. material reduction and energy optimization. These are generally good, though alone are not sufficient from a sustainability perspective. They also risk leading to the "rebound effect," which is the idea that improvements on a per-unit basis can lead to greater overall impacts due to increased volume that is enabled by, e.g., reduced cost that stems from the improved efficiency, see, e.g. (Binswanger 2001). While product innovation has traditionally focused on the former with occasional glances towards the latter (Isaksson et al. 2009), the movement in industry is now towards the design of artifacts and services together – often referred to as product-service systems (PSS) – and presents an opportunity for these two opportunities to be considered and improved in tandem (Isaksson et al. 2009; Maxwell et al. 2006).

1.1 Aim and Scope

This paper endeavors to contribute to answering the following question: How can sustainability considerations be better integrated into existing product innovation working environments, especially with regards to pursuing a product-service system approach?

1.2 Method

This paper presents ideas that have been collected through several research projects. As such, it draws from research that included the following methods and techniques:

- A broad survey of literature has provided an opportunity to explore the related topics and specifically focus on the intersection between these key topics, in order to better understand the past and present thinking within the research field.
- Interviews and interaction with people working within the area of product innovation were conducted in order to better understand and describe the state of practice in industry.
- Participation in and facilitation of workshops with development teams with companies involved in these research projects have provided insights in how to aid companies in including sustainability in their thinking around product innovation.

This paper is based on the idea that research into design processes cannot be re-created or tested with a control group. In practical research terms, every design project is unique because of a unique set of needs in an ever-changing global context being addressed by a single design group. Furthermore, there is no "correct" or even "best" solution, as this will change from user to user or context to context. This is the essence of the idea of "wicked problems" introduced by Rittel and Webber relating to planning with regard to social problems, where they see "social processes as the links tying open systems into large and interconnected networks of systems… it has become less apparent where problem centers lie, and less apparent where and how we should intervene even if we do happen to know what aims we seek" (Rittel and Webber 1973). In this regard, case study research is valuable because it allows for research topics to be defined broadly while potentially considering multiple variables and relying on multiple sources of evidence (Yin 2003). In recognition of the need for a new approach to this type of research, Blessing and Chakrabarti (2009) put forth a Design Research Methodology (DRM). The DRM and its methods provide guidance for planning and implementing design research, thus providing a more rigorous approach to research.

2 Related Areas

Concepts in this paper draw upon three broad topics: (1) sustainability, (2) product innovation, and (3) product-service systems. This section presents briefly each of these, as well as an additional area that is emerging as a combination of them: sustainable product innovation.

2.1 Sustainability

In recent decades, numerous reports, studies, theses, articles and books have been published documenting impacts and opportunities, e.g., species loss (Millennium Ecosystem Assessment (2005), resource constraints (Gordon et al. 2006), and the business opportunities for those aware of sustainability issues (Willard 2002). The Brundtland definition of sustainable development (Brundtland 1987) puts forth an attractive vision, but leaves a significant gap for the business need to be operational. This has lead to many attempts to clarify the concept of sustainability; one of which is a framework for strategic sustainable development (FSSD) based upon a five-level model that can be used to plan in any complex system. When it is used to provide guidance towards a sustainable human society (i.e. "human society within the biosphere"), it is referred to as the framework for strategic sustainable development (Holmberg and Robèrt 2000).

Three key aspects of the FSSD make it well-suited for use in both strategic and operational contexts.

- Five level structure, clearly distinguishing between the system, the definition of success, strategic guidelines, actions, and tools
- Unique definition of success in basic principles for sustainability
- Backcasting from a desired future (contrasted with forecasting current trends only)

Combining backcasting with this unique definition of success results in "backcasting from sustainability principles" allowing for strategic decision making that promotes flexibility, movement towards a sustainable future, and appropriate allocation of resources.

The term "sustainability" in this paper, then, refers to global socio-ecological sustainability. It does not, unless specifically stated, refer to the sustainability of some other (sub-) system, e.g., a company.

2.2 Innovation

Innovation, generally, refers to new products, processes or ideas that are put into use in the world. "Innovation" differs from "invention" which is the creation of those new products or processes, in that innovation implies inventions that are put into practice. Schumpeter lists five types of innovation: new products, new methods of production, new sources of supply, exploitation of new markets, and new ways to organize business (Fagerberg et al. 2006). In this paper, the term "product" is in line with the ISO definition and refers to "what is sold" and thus not only the physical artifact:

> *A product is an output that results from a process. Products can be tangible or intangible, a thing or an idea, hardware or software, information or knowledge, a process or procedure, a service or function, or a concept or creation.*

Innovation literature frequently comes from the social sciences with roots originating with, e.g., Schumpeter. Innovation references also originate from within the field of engineering, e.g. (Roozenburg and Eekels 1995; Ulrich and Eppinger 2008). One related observation is presented by Kline and Rosenberg:

> *Economists have, by and large, analyzed technological innovation as a "black box" – a system containing unknown components and processes. They have attempted to identify and measure the main inputs that enter that black box, and they have, with much greater difficulty, attempted to identify and measure the output emanating from that box. However, they have devoted very little attention to what actually goes on inside the box; they have largely neglected the highly complex process through which certain inputs are transformed into certain outputs.*
>
> *Technologists, on the other hand, have been largely preoccupied with the technical processes that occur inside that box. They have too often neglected, or even ignored, both the market forces with which the product must operate and the institutional effects required to create the requisite adjustments to innovation.*
> (Kline and Rosenburg 1986)

It is often challenging to arrive at a shared vocabulary between these different perspectives. This paper attempts to draw on literature from social science and engineering perspectives.

2.3 Product Service Systems

The concept of product-service systems (PSS) emphasizes a shift in focus from selling only a physical artifact or service to selling the result of a combination of the two. Definitions of PSS typically include reference to increased competitiveness of PSS providers and often refer to reduced environmental impacts.

Tukker presents eight types of PSS, divided into three categories: product-oriented, use-oriented, and result-oriented (Tukker 2004). Tukker, Tischner and Verkuijl (2006) have explored the opportunities for environmental improvement with regard to these eight types of PSS, suggesting that all eight types are usually, but not necessarily, associated with improved environmental performance. Of the eight types, some are believed to have the opportunity for more significant environmental improvement than others, with the function-oriented type having the most significant opportunities. This eighth type, functional result-oriented PSS, leads into the idea of "functional product development" described by Isaksson et al. (2009) as having the objective of "developing the solution (i.e. any combination of hardware, software, services, etc.) to customer needs that create value for the customer."

2.4 Sustainable Product Innovation

There is significant research in a variety of areas closely relating to sustainability in product innovation. Recently, work was done at Imperial College focusing on Sustainable Product and Service Development (SPSD) that reviewed many approaches to sustainability in product development and resulted in an approach emphasizing functional and systems thinking (Maxwell et al. 2006). Ecodesign emphasizes bringing ecological issues into the product innovation process; see Karlsson and Luttropp (2006) for an introduction, as well as closely-related concepts like Design for Environment (DfE). The present work differs from those by utilizing the framework for strategic sustainable development mentioned in 2.1, thus providing a different perspective with regard to the sustainability component with potentially different results.

There are various approaches to design (more broadly than product development) that also bring in sustainability-related thinking, e.g., Cradle-to-Cradle or Biomimicry. Here, emphasis is placed on radical innovation through outside inspiration. Cradle-to-Cradle, with the mantra "waste equals food," emphasizes the need for technical systems to operate in cycles, and highlights the concept that "eco-efficiency only works to make the old, destructive systems a bit less so" (McDonough and Braungart (2002). Biomimicry suggests that nature has been innovating for millions of years, and that there is a huge amount of inspiration to be explored by human designers (Benrus 1997). These two examples are mentioned because they strongly relate to the idea of using sustainability thinking to drive innovation.

3 Towards Sustainability-driven Innovation through Product-Service Systems

Section 3.1 presents views on how sustainability considerations are currently included in product innovation processes. Section 3.2 develops the case for using, and then presents ideas for how to work towards, sustainability-driven innovation through product-service systems.

3.1 Observations on Sustainability in Swedish Product Innovation

This section first reflects on some motivations for companies wanting to include sustainability in their product innovation processes, followed by some ways that they are including sustainability in those processes and some of the justifications they provide for doing so.

Motivations for Including Sustainability

Companies include sustainability criteria in their product innovation processes primarily for one of these reasons: 1) legislation, 2) cost reduction (e.g. resource efficiency), or 3) employee interest in "doing good."

Certainly the Swedish companies involved in this work include sustainability aspects at least to the extent that they must in order to comply with legislation. Sustainability criteria that overlap with cost savings (e.g. efficiency of resource use or energy) are also very likely to be considered. Other sustainability criteria that do not have direct effects on cost are much less likely to be considered; though aspects that can have indirect impacts on company success, e.g., through the company's image are being considered with greater frequency.

The origination of sustainability from legal requirements or employee interest often leads to sustainability considerations being perceived as an extra expense, i.e. one more requirement that competes for resources.

In both business-to-consumer (B2C) and business-to-business (B2B) situations, customers are increasingly demanding sustainability be considered. In B2C it is often in the form of eco-labels or other identifying factors that provide peace of mind to the consumer, while in B2B situations it frequently relates to procurement demands by the purchasing company to reduce risks, e.g., of not being in compliance with environmental legislation.

Ways of Including Sustainability

In response to the way sustainability aspects are beginning to be required of companies, sustainability aspects are being added into product requirements, e.g., compliance with materials lists that say certain substances are not to be used in a product itself or the manufacturing processes for the product; carbon emissions over the life of the product must be estimated and held at or below a certain level; or the working conditions of suppliers must meet certain requirements. Some of these have been around for decades (e.g. material lists), while others are more recent (e.g. social aspects at suppliers).

Innovation processes must then take these additional requirements into consideration. This further limits (e.g. beyond technical limitations) the design space in which product developers are able to create solutions, and may draw resources away from other types of improvements that could be made. This adds to the cost of the innovation project, putting additional constraints on the already stretched allocation of resources.

Justification for Including Sustainability

These approaches typically lead to attempts to show how sustainability efforts reduce costs or increase revenues, and to argue that when fully considered sustainability aspects do not increase overall costs for the company. Theoretically, this is done at a product level through, e.g., life-cycle costing (LCC), total-cost accounting (TCA), or full-cost accounting (FCA); see, e.g. (Norris 2001; Shapiro 2001). Willard has written on the effects of sustainability at the firm level, and suggests that there are significant economic impacts on a company's bottom line from incorporating sustainability aspects that relate to, e.g., staff retention, attraction of the best talent, etc. (Willard 2002). Many companies that have been involved in these research projects are aware of these approaches, but do not appear to have them integrated into standard procedures.

Summary of Observations

The chain of thought presented in this section suggests that companies include sustainability considerations either because they are required by legislation, out of some sense of greater good, or in order to attract or retain customers and staff. All of these are fine reasons to include sustainability considerations, and likely contribute to a company's success. However, this chain of thought does not get directly to the main motivation for industry: profitability. Rather, there is an indirect journey that leads back to profitability. As with the FSSD referred to in section 2.1, "sustainability" is at the "success" level. However, for companies, "success" is not "global socio-ecological sustainability," but rather "profitability." Awareness of sustainability issues and the strategic use of them can certainly support a company's efforts to be profitable.

Innovation is a significant factor in profitability: the ability to identify and successfully take to market new products, to find new and better ways to produce physical artifacts and to deliver services, etc. directly support competitiveness and profitability for firms. And, innovation that supports development of society towards a future that 'can be' (i.e. a sustainable society) should have an inherent overall advantage over innovation towards a future that 'cannot be'. Assuming this is true, there is an opportunity for sustainability to drive innovation processes in companies that leads to profitability. What is missing, then, is the competence to use sustainability, and especially a strategic sustainability perspective, to guide and accelerate innovation processes.

3.2 Sustainability as Driver of Innovation

The Case for Sustainability as Driver

Sustainability as described in section 2.1 asks what is necessary in order for human society to not systematically degrade the social and ecological systems that it depends upon, and suggests that society ought not to do things that potentially risk long-term existence. This way of thinking about sustainability can be used to drive innovation by guiding incremental and radical innovations in either products or processes (e.g. reduced material or energy use by a product or increased efficiency in production processes). This thinking can also drive incremental and radical innovations in business models, market conditions and societal institutions which opens up for the meeting of human needs in ways that mean significantly reduced negative environmental or social impacts.

Sustainability-driven innovation is different than "innovation for sustainability," which implies that the innovators are interested in pursuing sustainability as an end goal. This is not typically the way companies do, or even legally can, define success. Rather, knowing about sustainability issues can help companies to be more successful on an increasingly sustainability-driven market.

Using a product-service system approach provides an opportunity for companies to reconsider how their artifacts, services, and combinations of these create value and generate revenue. Pursuing a PSS does not necessarily explicitly demand a sustainability focus or even awareness, and it does not necessarily imply an improved sustainability profile. Rather, a PSS-approach opens up to new ways of thinking which are inherently in less contradiction to a sustainable society than more traditional approaches focused only on generating revenue from the sales of physical artifacts. This is because a PSS-approach opens the possibilities to generating revenue based on the provision of specific functions that meet needs rather than generating revenue based on the sales of those physical artifacts. Revenue based on function is further enhanced through sustainability-related initiatives such as dematerialization, consideration of closed-loop product life cycles, minimization of operating costs that are often indicative of negative environmental or social impacts, etc.

Making Sustainability the Driver

Section 3.1 presents observations of the day-in and day-out of sustainability aspects in product innovation in some Swedish companies: there exists a core product, there is a desire to improve the product both in terms of meeting evolving customer needs and in terms of profitability, and there is an interest or a need to maintain or improve sustainability performance. With that in mind, and also keeping in mind Section 2.4, which briefly introduced other existing innovation-based design approaches (with Cradle-to-Cradle and Biomimicry as specific examples), the following are thoughts on how innovation processes can become more sustainability-driven.

Backcasting when Developing Support

The challenge when developing support for innovation processes is that with regard to sustainability, there is a sense of needing the radical changes that can be inspired by more radical concepts. On the other hand, the challenge of integrating support into existing product innovation working environments is that there are established routines and tight timeframes for innovation projects; asking for a radical re-thinking of how a product should or could function is simply not possible given limited resources. Product developers ask for a simple tool that guides them to the right material choice; e.g. aluminum requires more energy to produce than steel, so steel should be used. This, of course, is a gross over-simplification of the life cycle impacts of the different materials, and is precisely why simple, well-intentioned guidance is problematic: the questions seldom have simple answers. People understand this: aluminum is lighter than steel, so using aluminum instead of steel in some applications will recover the extra energy used in production, eventually having a better overall performance with regard to energy use. However, the best design may depend significantly upon user behavior, thus an apparently simple question becomes a wicked problem as described in section 1.2.

Support concepts must acknowledge the reality of the present product innovation working environment, including resource (e.g. time) constraints as well as product performance obligations. This naturally tends towards an incremental approach to improving the sustainability performance of products. At the same time, there is an urgency to provide support that is capable of meeting the ever-higher demands of the global context. In light of this, there is an opportunity to use a backcasting approach when developing support tools and methods. This would entail developing support that considers both the immediate decisions that product developers are being asked to make, and also using that support to lead the product developer's thinking into new areas.

The short-term steps involve providing support tools and methods that companies need to continue exploring a PSS mindset may not result immediately in function-based innovation (since function-oriented products are only one type of PSS). The long-term is about working towards function-based innovation so that revenue streams can evolve to be based on sales of function – with its associated potential benefits for global socio-ecological systems.

Here the suggestion is that the backcasting approach should be used by researchers to develop support methods and tools. Furthermore, based on the assumption that pursuing function-based products is a very attractive opportunity that combines society's need to pursue sustainability with the business need to be profitable, the suggestion is that the vision that is backcast from should be a product innovation working environment that is focused on functional product innovation.

Expand from Sustainability Constraints to Sustainability-driven Innovation

As described in 3.1, sustainability is often incorporated into product innovation working environments as an "add on," e.g., through product or process requirements that serve as filters to reduce the number of ideas or concepts until only the "more sustainable" (i.e. the options with the fewest known environmental impacts) remain.

To a greater or lesser extent, adding sustainability-based design requirements and incorporating methods and tools to existing product innovation processes are ways of comfortably introducing sustainability into those environments. However, as the easy opportunities for improvement with regard to sustainability are implemented (i.e. the "low-hanging fruit" are "harvested"), continued improvement with regard to sustainability aspects is more difficult. After the easy opportunities are exhausted, then there is a need/opportunity for sustainability to proactively drive innovation.

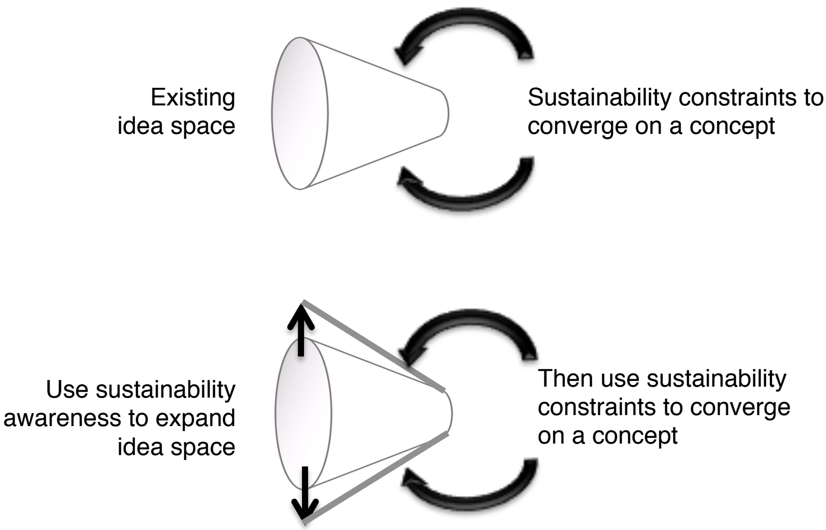

Figure 1: Using sustainability knowledge to expand idea space prior to using sustainability knowledge to constrain selections.

Here it is suggested that sustainability can drive innovation by opening up the idea space during idea generation, i.e. contributing to the "divergence" that occurs in earlier stages, before sustainability aspects are used as a filter to "converge" into a final product. An example of this is provided by Ny et al. (2006) through a waterjet cutting machine, where they describe a way in how to do this by modeling a current system and then looking at it in an anticipated future in which the market is increasingly sustainability-driven.

Create value by optimizing at a broader system level

Expanding the peripheral perspective of people working with innovation can lead to opportunities for capturing value that is otherwise outside of their scope. This is because there is frequently an emphasis on the optimization of sub-systems, while higher level systems remain sub-optimized: focus is on tweaking the details of lower-level systems, while opportunities for significant higher-level system improvement are missed. This is in line with what Bey and McAloone (2006) suggest when discussing the role of ecodesign and LCA in PSS development: that a PSS approach inherently promotes thinking at a higher system level.

A waterjet cutting optimization project illustrates this: the first efforts in the project related to building detailed technical models of the machines and machines parts, which were used to better optimize the weight of the parts, and thus improving the energy efficiency of the machine, e.g., an opportunity to reduce the weight of moving parts by 30 percent lead to overall system improvement (Byggeth et al. 2007).

Additionally, outside of the scope of those early technical improvements, was the opportunity to optimize the broader system with regard to use of sand as an abrasive in the process. The weight optimization of machine parts is at a more focused system level, thus involving a smaller number of actors, and thus easier to modify. The opportunity to optimize the abrasive was out of the scope of the initial focus, and when explored, involved a significantly larger number of actors. There is, however, economic value to be captured and environmental improvement to be made specifically by reducing transportation related to the sand. One can assume the current situation happens as it does today because it optimizes the economics at a certain level. However, as the market becomes increasingly sustainability-driven (e.g. increased transportation costs due to energy price increases, carbon-related taxes, etc.) opportunities to optimize at a higher system level will become more economically rational.

This example is provided as an illustration of how broadening system boundaries can lead to improvement: first the machine itself was optimized. Then this example broadened system boundaries to consider how to optimize consumables related to the machine, The next opportunity to broaden system boundaries involves a move towards a PSS based offer (selling the function of cutting, instead of selling machines) by further extending system boundaries, e.g., to better consider how users interact with the waterjet cutting machine and the specific contexts of how the machine is used.

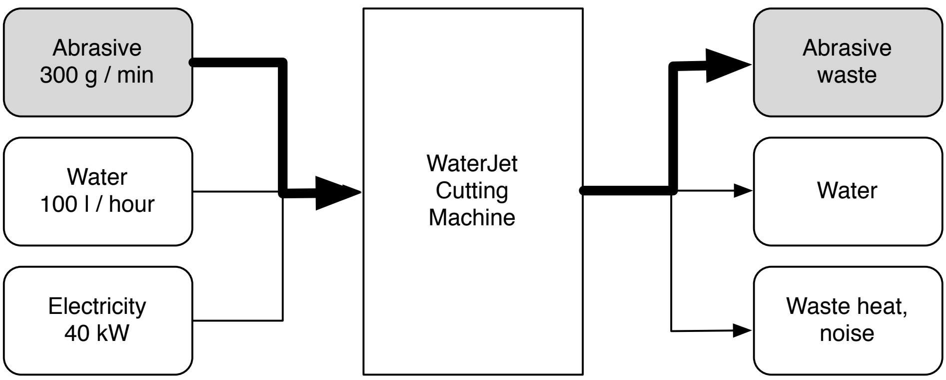

Figure 2. Expanding the view of the Waterjet Cutting Machine to include other required energy and material flows in the cutting process. The abrasive is highlighted due to having the greater environmental impacts.

Capturing the value created by optimizing at higher system levels is challenging, particularly with business models focused on the sales of physical artifacts. However, Thompson et al. present an example that appears poised for capturing value at this higher level: long-life light tubes that reduce total cost of ownership by eliminating operating costs associated with changing the light tubes at the end of their useful life (Thompson et al. 2010). This value is not typically considered in the development of physical artifacts, and communicating it to customers is also challenging. The PSS approach, however, opens possibilities for win-win-win situations for the light-tube providers, users and (because of improved sustainability-performance) society.

Innovate the offer, not the artifact

The case presented by Thompson et al. also shows that there is an opportunity to use an existing product to focus on a new approach to providing the function that customers want. In the case of long-life light tubes, the physical artifacts have a specific attribute (a working life several times longer than the average light tube) that (potentially) offers a significant sustainability advantage. This case suggests that in order for the sustainability advantage provided by the attribute of that product to also be made into an economic advantage, the business model around the product needs to shift towards a function-based offer of providing light, rather than remaining focused on selling the physical artifact.

4 Results and Conclusion

This paper aims at supporting the inclusion of sustainability considerations in the product innovation process by articulating how sustainability can be a driver in the innovation process, specifically through a product-service system approach. This work contributes to understanding with regard to theory about how sustainability-driven innovation can occur through product-service systems within the broader research field, as well as how to apply that understanding to the state of practice in industry today in order to realize more sustainable PSSs.

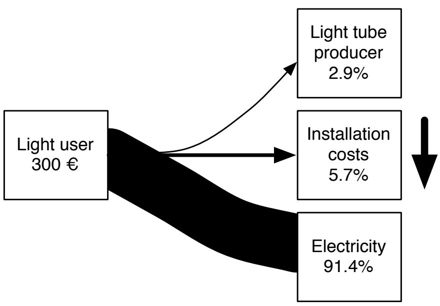

Figure 3a: Total customer costs for light during 12 years with 4 standard-life light tubes sold as the product.

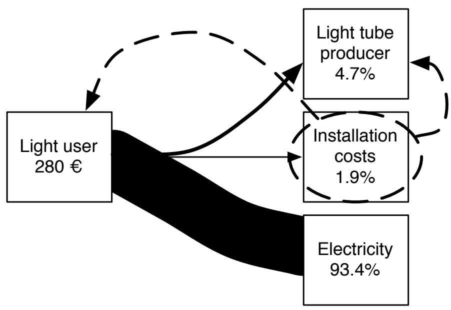

Figure 3b: Total customer costs for light during 12 years with one long-life light tube as the basis for a PSS-offer.

There is an opportunity to improve sustainability performance of a PSS and increase customer value by broadening the scope in product innovation working environments to allow for increased consideration of opportunities in two areas highlighted in this paper. First, technical systems can be optimized at higher system levels, e.g., as in the case of abrasives with the waterjet cutting case. Second, business models can be modified to focus on communicating value through function, especially with regard to products that have sustainability attributes as demonstrated in the case of long-life light tubes. For those working in the area of sustainability, "sustainability" often becomes the primary motivating factor. While a business cannot be sustainable if it is part of an unsustainable society, the perspective is different from within the business world. Thus, companies are typically more interested in innovation than sustainability, for the ability to innovate is what allows the company to sustain itself: changing customers, offering new products/services, expanding into new markets, etc. In recognition of this, this paper has demonstrated and developed ideas around how sustainability can be used to drive those innovation processes through product-service systems that companies rely upon, while also supporting global society's movement towards sustainability.

5 Future Work

Future efforts building upon this work could include:

- Clarifying the argument for shifting inclusion of sustainability aspects from a "do less bad" approach that only emphasizes quantifying and reducing known negative environmental impacts, and moving towards a methodology where sustainability is driving innovation processes;
- Further reviewing and summarizing sustainability aspects of PSS, with a specific look at the FSSD's role in understanding and analyzing the value PSS can bring to global sustainability work;
- Continuing to support working towards sustainability-driven innovation through PSS by developing methods, tools and frameworks; and
- Exploring how socially oriented aspects, and in particular user interaction with the product, can be better considered during product innovation, specifically in the context of a PSS based offer, where user behavior has very significant implications for the economic viability and sustainability performance of the offer.

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Paper D

Benefits of a Product Service System Approach for Long-life Products:

The Case of Light Tubes

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Benefits of a Product Service System Approach for Long-life Products: The Case of Light Tubes

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Abstract

Products designed for long-life often have significant potential for better sustainability performance than standard products due to less material and energy usage for a given service provided, which usually also results in a lower total cost. These benefits are not always obvious or appealing to customers, who often focus on price. Long-life products are therefore at an inherent disadvantage: due to lower volume of sales that results from the products' longer-life, the margins (price) often need to be higher. In this paper, we demonstrate that when the revenue base is shifted to be the service of light (instead of the sales of light tubes), there is an opportunity for a "win-win-win" for the light user, the long-life light provider and society. Through a product-service system approach, resulting in a well-communicated total offer, the full array of benefits becomes clearer to the customer, including that they avoid the high initial cost.

Keywords

sustainability performance, long-life products, product-service system, value chain, modeling

1 Introduction

This study has come about through a partnership between researchers at BTH and Aura Light International AB (Aura) which produces long-life fluorescent light-tubes with a life-length that is three times longer than the industry average. Like many firms, Aura Light is increasingly aware of the opportunities and risks being presented by an increasingly sustainability-driven market (Willard 2002; Berns et al. 2009). The Sustainability Assessments research team at BTH has specific competence with strategic sustainable development (SSD) (Broman et al. 2000; Robèrt et al. 2002) and application of SSD in the context of product development (Hallstedt 2008; Ny 2009). Due to the long-life nature of Aura's product, there are challenges when competing with producers of "standard" life-length light-tubes, i.e. Aura has 1/4 as many opportunities to generate revenue from the sales of a physical product as its competitors. From a sustainability perspective, the long-life product is obviously worth exploring since it reduces material flows by approximately one-fourth.

The concept of product-service systems (PSS) has been defined as a system joining products and services in order to meet customer needs. It emphasizes a shift in the focus from selling physical product to selling the function provided by this combination of products and services. Definitions of PSS typically include reference to increased competitiveness of PSS providers. Some definitions do not explicitly include reference to reduced environmental impacts (e.g. (Manzini and Vezzoli 2003; Wong 2004). However, PSS definitions frequently also include reference to reduced negative environmental impacts (e.g. Goedkoop et al. 1999; Mont 2004; Baines et al. 2007).

Tukker has articulated two concrete questions that he suggests are often overlooked when analyzing PSS: First, "which factors determine whether a PSS business model is the best way to create value added?" and second, "which factors determine whether a PSS business model per se generates less material flows and emissions than the competing product oriented models, and thus provides incentives for sustainable behavior?" (Tukker 2004). These two questions (creating added value and reduced material flows and emissions) make a PSS approach for Aura Light an interesting consideration.

This paper explores the concept of product-service systems as a potential way of overcoming this contradiction between reduced number of revenue-generating opportunities, desire for increased revenue, and demand for less negative sustainability impacts. Through the example, this paper will demonstrate the potential for a company with an existing long-life product (a physical product designed for a significantly longer average useful life than a "regular" product) to consider if it can have a competitive PSS-offer.

2 Methods

Two approaches to selling the service of light are compared: the first a producer of standard-life light-tubes, and the second a producer of long-life light-tubes. For each approach, the economics of the approach are considered from the perspective of the user and the primary provider. The socio-ecological sustainability implications (i.e. broader society) are also considered. Thus, this paper considers four scenarios from three different perspectives.

Four scenarios:

- Standard-life light tube sold as a physical product
- Standard-life light tube sold as a PSS offer
- Long-life light tube sold as a physical product
- Long-life light tube sold as a PSS offer

Three perspectives:

- Customer (economic - cost of light)
- Producer (economic - profit)
- Society (socio-ecological sustainability)

The prices and costs here are provided for illustrative purposes and are not actual figures from a company. The researchers were "kept in the dark" in order to not compromise sensitive information, and thus these figures come from a survey of the lighting industry. The following assumptions are made for this analysis:

- Long-life light-tubes lasts 4x longer than standard-life light-tubes (12 yrs vs. 3 yrs at 4000 h/yr)
- Sales price is 4x higher for long-life light-tubes (10 € vs. 2,50 €)
- Cost to replace a light-tube (including labor, disposal fee, and downtime) is 5 €
- Light fixtures are pre-existing (so not included here)
- Both light-tubes use them same amount of electricity
- Both light-tubes provide the same amount of light
- Electricity cost is 0,10 €/kWh
- Annual discount rate of 3%
- No "rebound effect" will occur because of a shift from product to PSS offer

2.1 Customer (Economic) Perspective

To answer Tukker's first question from the customer's perspective, a simple life-cycle cost model considers the economic aspects of the four scenarios from the customer (light-user) perspective. Here the cost to the customer for light-tubes (as either a purchased product or a PSS) and replacement of the light tubes are considered for providing 4000 hours of light per year for a period of 12 years. A discount rate is included due to the long time period considered. Pricing alternatives are not optimized in any way; the prices used are only to demonstrate the way in which long-life products are able to capture and re-direct value to the producer and user.

Two criteria are considered for the customer: cost in the first year, and total cost for light over 12 years. Twelve years is used because it is the lifetime of one long-life light tube.

A price for the annual service of using a light-tube is set to 1€. This rate was obtained by setting the net present value of the revenue generated by a long-life light-tube that is provided as a PSS-offer for 12 years equal to the net present value of the revenue generated by selling one light-tube that has an expected life of 12 years.

2.2 Producer's (Economic) Perspective

For a PSS-offer to be possible, it must also be profitable for the offer provider in addition to being attractive to the customer. In this case, the long-life light tube producer is trying to lower total cost to the customer while capturing for itself enough of the value realized through that cost savings to be competitive with the producers of standard-life light-tubes. This is represented by exploring if the customer savings is significant enough to compensate for the reduced number of light-tubes the customer must use to meet its need for light. All of the costs incurred by the customer are mapped, the costs that can be reduced by the long-life offer are noted, and a decision is made regarding whether or not the PSS-approach is profitable. Note that company data is not able to be published, so illustrations are used to demonstrate the concept.

2.3 Society's (Sustainability) Perspective

As a prelude to answering Tukker's second question regarding reduced material use and emissions, an approach is taken that incorporates a strategic sustainability perspective in order to not only quantify material and emission reductions, but also to be sure that the scenario is not causing other sustainability issues. This is done by using an approach called "backcasting from sustainability principles" that states there are four basic principles that will be met by a society that is sustainable (Azar et al. 1996; Broman et al. 2000; Holmberg and Robèrt 2000; Ny et al. 2006). These basic principles state that in a sustainable society, nature is not subject to systematically increasing:

1. Concentrations of substances extracted from the earth's crust;
2. Concentrations of substances produced by society;
3. Degradation by physical means, and
4. In that society, people are not subject to conditions that systematically undermine their capacity to meet their needs.

Since these are principles for sustainability of global human society, we assume that companies, products, or PSS that comply with these conditions (and thus do not contribute to society's sustainability problems) will have a competitive advantage compared to those that do not meet these principles.

For the sustainability assessment, a strategic life cycle management (SLCM) approach is used to consider how the scenarios comply with basic principles for global socio-ecological sustainability during each of the life cycle stages (Ny et al. 2006). This approach is used in order to first take a strategic overview of the sustainability implications before attempting to provide a quantitative response to Tukker's second question regarding energy and material flows; this allows a full sustainability perspective so that as some challenges are addressed (e.g. material and energy reduction), other sustainability challenges are not created unintentionally. The SLCM approach is implemented by using a strategic life cycle matrix to identify any differences between the offers being considered.

The columns in the matrix refer to those basic principles for a sustainable society. The rows in the matrix refer to life cycle stages of the product or PSS. This allows for the identification of any current or future sustainability challenges related to the life cycle of the product. The matrix is shown in Figure 1.

<table>
<tr><th></th><th>Principle 1</th><th>Principle 2</th><th>Principle 3</th><th>Principle 4</th></tr>
<tr><td>Materials</td><td colspan="4" rowspan="5">List of aspects of the offer that are not in compliance for each life cycle stage and sustainability principle</td></tr>
<tr><td>Production</td></tr>
<tr><td>Packaging & distribution</td></tr>
<tr><td>Use</td></tr>
<tr><td>End of Life</td></tr>
</table>

Figure 1: Strategic Life Cycle Management Matrix

One matrix is completed for each product or PSS being considered, and if differences are identified, then a more in-depth assessment can be conducted to consider the trade-offs. This step is in realization that "sustainable behavior" is not only about reducing material flows and emissions, and that by focusing only on these two items there is a significant risk of sub-optimization of sustainability performance.

After obtaining a strategic overview from the matrix, there is an opportunity to go into more detail to allow for the quantification of relative environmental impacts. Life Cycle Assessment (LCA) (ISO 2006) is a tool suited for such a quantitative analysis, and has been referred to as a complementary tool in PSS development in other places (Bey and McAloone 2006). The LCA software tool Simapro, utilizing EcoInvent (EcoIvent Centre 2007) data, along with some assumptions with regard to transportation and energy, is used to obtain some order-of-magnitude estimates regarding environmental impacts due to reduced material use from the long-life product over the product's life cycle. While this is not an ISO 14040-certifiable LCA (that process requires a much more rigorous process for goal setting and scoping, data collection and verification, and impact assessment), this can be performed in a few hours to obtain an approximation of the improvement across the product's life cycle.

3 Results

3.1 Results of Economic Assessment

The boundaries of this study with regard to the value chain focus foremost on the producer of the light-tube and the light user. Because it requires four standard-life light tubes and the associated activities throughout their life cycles to match the useful life of one long-life light tube, the costs throughout the value chain recur four times for the standard-life light tube for every one time in the long-life light tube's life cycle. This is illustrated in Figure 2.

Light Customer Perspective

Economic considerations for the light user are presented in Table 1. Regarding initial cost, the long-life light tube sold as a product has a significantly higher cost than the other scenarios: 15 € (10 € for the light-tube in addition to the 5 € cost of tube installation) compared to either 7.50 € or 6 €.

Users of light have lower costs by using the long-life tubes, either by purchasing them outright or by accessing the light tubes through a PSS-offer. In this example, the 15 € difference between the total for standard-life and the total for long-life is simply the three installations (5€ each) that are not required with the long-life option. This difference remains significant when the net present value is considered, so here it seems that either of the long-life scenarios would be preferred by the customer.

Considering both the initial cost and the full costs over 12 years, the long-life light tube offered as a PSS appears most attractive to the customer.

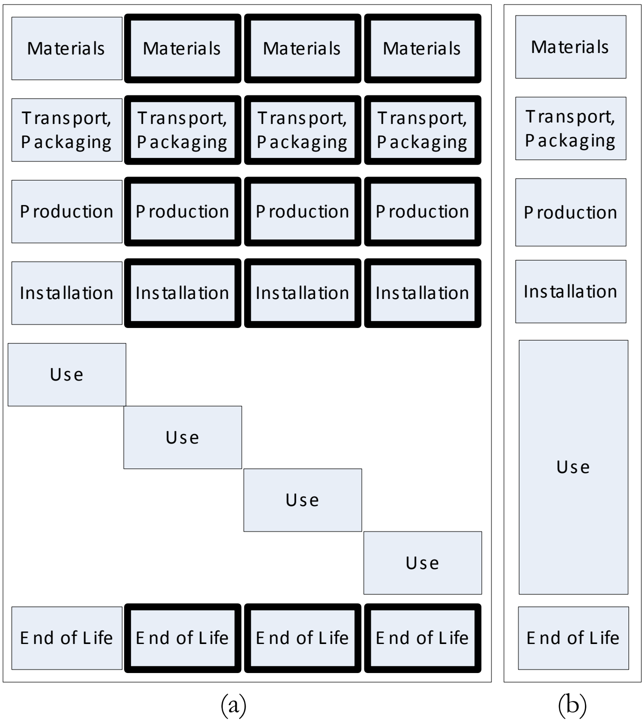

Figure 2: Activities where costs are incurred over the light tube life cycle when providing 48 000 hours of light with standard-life light-tubes (a) compared to 1 long-life light tube (b). Bold boxes show costs incurred in (a) only.

Light Producer Perspective

The long-life light-tube producer's challenge is to do two things at the same time: first, to lower costs to the customer in order to make the long-life offer attractive, and second to increase the revenue that the customer is paying for the light-tubes (again remembering that the long-life producer is selling one-fourth as many tubes as a standard-life light-tube producer). Actual numbers from the company are confidential, but this concept is illustrated in Figure 3. Electricity costs are also included in the diagram in order to show the total life cycle costs of the customer (i.e. electricity is greater than 90% of the customer's cost).

Table 1: Customer costs of light-tubes and light in € over 12 years (48 000 hours of light).

Customer Perspective: Costs

	Standard life		Long life	
Year	Product	PSS	Product	PSS
2010	7,50	6,00	15,00	6,00
2011	0,00	1,00	0,00	1,00
2012	0,00	1,00	0,00	1,00
2013	7,50	6,00	0,00	1,00
2014	0,00	1,00	0,00	1,00
2015	0,00	1,00	0,00	1,00
2016	7,50	6,00	0,00	1,00
2017	0,00	1,00	0,00	1,00
2018	0,00	1,00	0,00	1,00
2019	7,50	6,00	0,00	1,00
2020	0,00	1,00	0,00	1,00
2021	0,00	1,00	0,00	1,00
Total	**30**	**32**	**15**	**17**
Net Present Value	**24,39**	**25,64**	**14,42**	**14,19**

For the light consumer and the light-tube producer, there is an opportunity for the long-life light-tube to be mutually beneficial because it captures value that is otherwise distributed throughout other actors in the value chain. In this example, the captured value includes:

- Savings by cost reduction due to changing tubes 1/4 as often (savings include e.g. the expense of manual labor and disruption to operations), and
- Increased efficiency of light provided per material/energy input (1/4 as much material required and 1/4 as much energy for production, transport, etc. excluding the use phase).

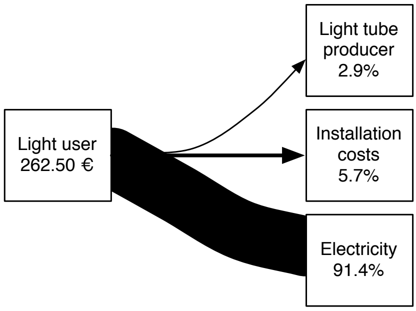

Figure 3a: Total customer costs for light during 12 year with a standard-life light tube sold as a product.

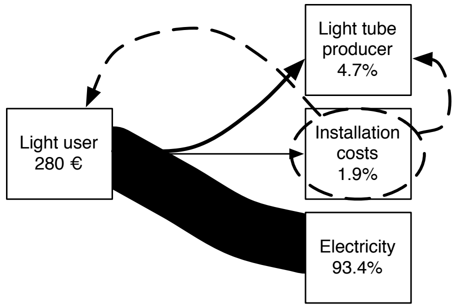

Figure 3b: Total customer costs for light during 12 year with a long-life light tube sold as a PSS.

3.2 Results of Sustainability Assessment

Strategic Life Cycle Management Matrix

Due its focus on a qualitative overview to identify all potential sustainability concerns, the SLCM approach provides no distinction between the standard-life and long-life light tubes. This is because the life-cycles of both light-tubes contain the same sustainability concerns from a strategic overview perspective. See an example of a partially completed SLCM matrix for light tubes in Table 2.

Based on this conclusion, one can then say that probably the scenario that has less energy and material flows is the "more sustainable" alternative. With the long-life product reducing the raw materials, manufacturing, maintenance (e.g. light-tube replacement) and end-of-life phases of the light-tube's life cycle by three-quarters, it clearly has environmental benefits over the standard-life light-tube (assuming that energy use for illumination is the same for both light-tubes).

Quantification of Environmental Impacts

Estimates are made using EcoInvent data in the life cycle assessment software tool Simapro. To make some quick estimates, these values were assumed:

- 150 kg-km of transport for light-tube components
- 100 kg-km transport of light-tube to customer
- 2400 kWh of electricity from the Swedish grid
- IPCC GWP 100a as the impact assessment method

This resulted in electricity during the use phase being about 94% of the environmental impact.

Then the electricity source was changed to the US grid, which resulted in the impacts due to electricity use being on the order of 99%. This assessment is sufficient for us to say that the global warming potential (using IPCC GWP 100-

year) of using the long-life tubes with "dirty" electricity is about 3% less than standard tubes, and on the order of 17% less on a "clean" grid. In this scenario, the GWP is reduced on the order of 10%, even though material use is reduced by a factor of 4.

Table 2: Example of an SLCM Matrix for light-tubes.

	SP1	SP2	SP3	SP4
Materials	Mercury Copper Lead	Solvents in marking ink	Land change due to mining	Worker safety
Production	Lead	Flame retardants Cleaning chemicals		
Packaging Distribution	Use of fossil-based plastics		Land use for transport	
Use	Use of fossil energy			Ballast noise
End of Life			Land change used for landfill	

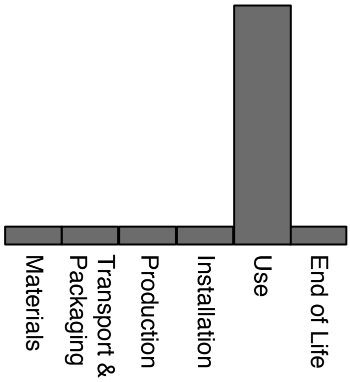

Figure 4: Approximate environmental impacts per life cycle stage of a long-life light-tube showing relative high impact during use phase.

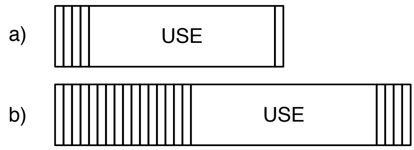

Figure 5: Environmental impact comparison between one long-life light tube (top) and three standard-life light-tubes (bottom). Vertical bars represent the life cycle stages in Figure 4. Top bar shows the long-life product, with 1/4 of impacts from stages other than use, compared to bottom bar that shows standard-life product. Impacts from use phase are the same for both.

4 Summary of Results

The authors choose not to go into further detail with the LCA because this is not a trade-off situation: the long-life light tubes win from the producer's economic perspective, the consumer's economic perspective, and a broader societal perspective (from fewer negative sustainability implications) and there is no need to more exactly quantify the extent to which a long-life light tube is "less bad" than a standard-life light tube. Furthermore, on a sustainability-driven market where costs related to material and energy flows are expected to increase, the benefits from minimizing those flows are only expected to increase.

If, in line with current practice, revenue comes from the sales of light-tubes, then the long-life producer earns more profit than standard-life producer and the customer has a lower total-life cost, but the customer balks at the high initial cost. It is only when the long-life product is used as the basis for selling light that the long-life producer really wins: the long-life producer has a higher profit and the customer has both a lower total life cost and an initial price similar to what is offered by the standard-life product. The trade-off is that the producer must then front the capital costs for production.

Table 3: Summary of assessments

	Standard Life		Long Life	
	Product	PSS	Product	PSS
Consumer (Initial cost)	Prefer: lower initial cost	Prefer: lower initial cost		Prefer: lower initial cost
Consumer (total cost for 48 000 hours of light)			Prefer: lower total cost	Prefer: lower total cost
Producer				Prefer: because customer prefers
Society (full sustainability)	no differences identified			
Society (reduced materials and emissions)			Prefer: lower material and energy flows	Prefer: lower material and energy flows

5 Discussion

This paper uses many of the same logical arguments in favor of a PSS approach that have been offered by early movers in this field. The contribution here comes from shifting the starting point of those arguments, particularly emphasizing that products designed for long-life gain competitive advantage through a PSS offer by capturing value that is otherwise distributed elsewhere in the value chain. Rather than having a regular product evolve into a PSS and then work towards longer-life, we start with a long-life product that gains competitive advantage by selling the function it provides: a different path to the same result.

5.1 Economics of Long-Life Products and PSS

Long-life products have the potential to capture value that can be shared between producers and consumers. However, consumers may hesitate at paying the price of the long-life tube that allows a long-life manufacturer to be competitive – remember that long-life producers have only a fourth as many products to sell, and thus must earn higher margins per light-tube to generate similar net incomes. Thus a PSS-approach based on offering the service of light is one possible approach for the long-life light-tube manufacturer. The example given here is only a limited PSS offer, and there is substantial more opportunity for a long-life light-tube provide to transition more towards the service-end of a PSS offer. This paper limits itself to a slight shift towards a PSS offer to make its point. The authors acknowledge that multitude of additional opportunities to shift even farther towards the service end of the PSS spectrum.

What needs to happen from a PSS-development perspective, then, are two things. First, to lower the cost to the customer, and second, to increase the revenue to the primary producer, So, the smaller the difference between these two (i.e. "primary producer revenue" – "user cost"), the more opportunity there is for the primary producer to make an offer that is attractive to the user. This is simply saying that PSS-developers need to look at broader life cycle costs of a PSS-offer, and not only the production costs within its own operation. Currently this idea that a long-life light-tube reduces life cycle costs is emphasized by Aura in its sales approach. Yet Aura still sells its light-tubes in a traditional way. This opens the opportunity to package both existing light-tube hardware and additional services into an offer to light users.

5.2 Assessing Sustainability

The methods used to assess the sustainability of concepts in this paper complement Tukker's implication that reduced energy and material flows leads towards more sustainable behavior. Tukker's assumption is generally correct with one significant caveat: that the materials and energy sources have the same types of sustainability impacts. If, for example, the long-life product in our comparison contained substances that are not included in the standard-life product in order to give it the long-life property, then a more thorough assessment of the implications of the different materials would need to be conducted. This is certainly the case when comparing other lighting technologies ranging from the soon-to-be-banned incandescent bulb to LEDs, with the range of rare metals they often require. An SLCM matrix for these alternative lighting technologies demonstrates significantly different results.

However, the two physical products (standard-life and long-life light tubes) compared in this example do not differ in any significant way with regard to the materials throughout the life cycle of the product. The same materials are used in each tube, only in different quantities. If instead, the comparison was between long-life fluorescent tubes, incandescent bulbs and LEDs, then the SLCM approach would have identified as a significant difference that fluorescent tubes use mercury, or that LEDs use other rare metals. Traditional approaches to only quantify the differences in material and energy flows may miss this point, or may unintentionally focus on energy reduction without awareness of sustainability trade-offs of doing so. The authors do not suggest that such a decision is a bad decision – rather only that it should indeed be a decision, and not an unintended consequence.

5.3 Value Chain Cooperation

A point to clarify is the difference between providing alternative financing methods (i.e. the long-life manufacturer providing financing options to eliminate the light consumer's balking at high initial cost) and having a PSS offer. The former does not provide an opportunity for the light-tube producer to capture the value that comes from eliminating the cost of replacing the light-tubes; it rather passes all of that value directly to the light user. By not only considering, but rather outright claiming for itself that value – and being willing to share that value with the customer – the long-life producer has the opportunity to be competitive with standard-life light-tube producers.

It is important to note that other value chain actors – particularly material suppliers for the light-tube production and service-providers who change the light-tubes– are likely to lose value when the long-life light-tubes are used due to the reduced number of light-tubes that are used. While it is outside the scope of this paper to consider the impacts of this, the authors suggest that there could be an opportunity to engage those extended value chain partners in discussions of opportunities for new innovations in the value chain to better adapt the value chain to a PSS offer so that value chain partners are not left behind or otherwise preventing the transition to a PSS offer.

5.4 Full System Perspective

The long-life aspect of the light-tube reduces the need for changing light-tubes, and this consideration follows Mont's (2001) suggestion that a PSS needs to take a full system perspective. Precisely by taking this full-system perspective, the long-life product identifies opportunities in the value chain to add value to the customer, and thus addresses Tukker's first point about determining the value creation of the PSS business model. Tukker's second point regarding reduced material flows is clearly addressed through the nature of the long-life product – and importantly – is addressed in this particular case without significant concern of a rebound effect.

Continuing to take a full system perspective, we must also acknowledge that the majority of both cost and environmental impact are due to electricity use. Throughout this paper we have not taken into consideration what either the producer or user might do to reduce costs/impacts related to electricity use, but rather have only assumed that electricity use for either standard-life or long-life light-tubes are the same. As part of a PSS-offer, certainly there could be opportunities for a "provider of the service of light" to incorporate ways to reduce lighting needs and further share the cost savings between the provider and user.

Other concerns related to long-life products should not be overlooked in the practical consideration of sustainability issues. One such consideration is technology change: with a usable life of up to 12 years, it is quite likely that lighting technology will advance during that time and become more energy efficient. With the vast majority of energy use (and thus arguably the majority of negative sustainability impacts) coming from the use phase, it is possible that "locking into" a technology with such a long life would result in increased energy use. A further shift towards the service end of the PSS approach would also further shift this burden from the user to the producer – whether good or bad, this is something to be aware of.

6 Conclusion

This paper extends the same logical arguments in favor of a PSS approach that have been offered by early movers in this field by shifting the starting point of those arguments. Here the emphasis is that products designed for long-life gain competitive advantage through a PSS offer by capturing value that is otherwise distributed elsewhere in the value chain. Rather than having a regular product evolve into a PSS and then working towards longer-life, it is possible to start with a long-life product that gains competitive advantage by selling function: this is a different path to the same result.

Specifically, this paper shows how value can be captured through cost-savings and then re-distributed directly to the consumer or the producer. Estimates of life cycle costs are made, including acknowledgement of the need to consider discount factors in economic analysis of products designed for long-life. This economic assessment addresses the life cycle costs of the acquiring the function of light from the user's perspective, and addresses in simple terms the economic viability of a PSS-offer from the light-tube producer's perspective.

The long-life manufacturer creates value by producing long-life products that reduce the need to replace light-tubes, and the challenge is to capture that value because it is not contained within the value offer with their current business model. The value the long-life manufacturer creates essentially lies in the hands of their customers who, of course, appreciate the value created since it reduces their lighting costs. However, those light consumers are not necessarily willing to share this value (savings from not needing to change light tubes) by paying a premium to the long-life producer. Therefore the producer must find opportunities to capture that value, and a PSS-approach provides such an opportunity.

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Paper E

Pursuing Sustainability through Servitization in Manufacturing Firms

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Pursuing Sustainability through Servitization in Manufacturing Firms

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Abstract

Product-service systems (PSS) have been proposed to simultaneously enhance competitiveness and foster sustainability. Yet despite the apparent strategic importance, "sustainable PSS" have essentially not been realized.

Based on literature and case studies, this article explores why "sustainable PSS" have not been more widely realized by manufacturing firms. Two overarching problems are identified to reaching this: The first problem is the multitude of challenges companies face when pursuing PSS and relate to the need for PSS to be both function-oriented and co-developed. The second problem is clarifying what "sustainable" means. Common definitions relating to e.g. "use less" or "factor x" reductions are not sufficient and not always necessary to reach sustainability; hence a robust approach to sustainability could be utilized here.

The movement towards "sustainable PSS" is complex and full of risk, and progress therefore appears slow as companies initially find their way in this new arena. However, companies and their value chains are developing service competence and delivery capacity. Complementing these efforts with a more robust approach to sustainability as proposed in this article will further enable them to implement "sustainable PSS".

Keywords

Product-service systems; strategic sustainable development; sustainable PSS

1 Introduction

Product-service systems (PSS) have been proposed to simultaneously enhance competitiveness and promote sustainability. Yet despite the apparent strategic importance, there are many who argue that goals related to these have not been realized. At the same time, sustainability issues are rising on the agenda of these firms (Berns et al. 2009; Nidumolu et al. 2009; Willard 2012). Product-service systems have been proposed as a solution to both of these challenges (Roy 2000; Manzini and Vezzoli 2001; Tukker and Tischner 2006). Although firms are increasingly adding services together with products (Neely 2007), the promise of more sustainable solutions is largely unfulfilled (Vezzoli et al. 2012).

Competition has had an impact on the way that manufacturing firms have developed, produced, and delivered products and services to customers since the beginning of the industrial era (Porter 1998; Marsili 2001; Isaksson et al. 2009). For the past century, manufacturing companies have focused design and development activities on realizing the technical and engineered aspects of physical artefacts (Pahl and Beitz 1996). As the business climate has changed during the twentieth century, industry has had to continuously adapt its approach towards the development of new products (Brown and Eisenhardt 1995). In recent decades, competition from global markets has driven manufacturing companies to reconsider the traditional concept of goods production with the realization that gaining competitive advantage and expanding market shares is not achievable purely through continuous technical improvements. It is instead necessary to develop closer relationship to the customer to gain a deeper understanding of expectations, needs, and perceived value (Woodruff 1997). This has forced firms to radically rethink their value offer, and to begin to consider themselves not only as product sellers but also as service providers (Vandermerwe and Rada 1988).

Initiatives such as Total Offers (Neely 2007), Functional Products (Alonso-Rasgado et al. 2004), Product-Service Systems (PSS) (Mont 2002; Tukker and Tischner 2006; Clayton et al. 2012), Service Engineering (Tomiyama 2001), and Integrated Product Service Engineering (IPSE) (Lindahl et al. 2006) reflect the shift towards these new offers. Subtle differences in these approaches exist, but hereafter in this paper these are referred to as PSS. This transition from goods-dominant logic to service-dominant logic involves a radical change both in how products are offered (Vargo and Lusch 2004) and in the way they are designed and developed (Baines et al 2007; Isaksson et al. 2009). The focus of the design activity shifts from the definition of new products to the re-organization of existing elements based on new needs and values (Morelli 2006). It is no longer the produced artefact that is the result, but rather the solution of which that artefact is part. This leads to a growing need to include service activity in the design space (Salvendy and Karwowski 2009). This implies that developing a PSS is more than simply choosing the best technical solution; it instead requires identifying the preferred combination of products and services that enable maximization of value for customers and stakeholders, which may also include more thoughtful consideration of property rights than is common in industrial practice currently (Hockerts 2008). With PSS the interaction between the provider and the customer (whether professional or private consumer) becomes more sophisticated. The consequence for the customer might be that a smaller organization now is needed for support, since this instead is provided by the supplier. Consequences for the provider of functions may be e.g. increased life cycle responsibility, new legislation for responsibility for through-life material management, ownership with rental agreements instead of sold hardware units, and increased involvement in the customer's business processes. (Isaksson et al. 2009)

One additional aspect of maximizing value is sustainability (Nidumolu et al. 2009; Berns et al. 2009; Willard 2012). Manufacturing firms are finding that it is no longer a matter of if, but rather how, to bring consideration of environmental aspects into both their corporate management (Porter and van der Linde 1995; Epstein 2008) and their product development work (Bras 1997; Boks 2006; Byggeth et al. 2007). These issues have continued to evolve through multiple generations (Roy 2000; Simons 2001) including pollution prevention (El-Halwagi 1997), ecodesign (Luttropp and Lagerstedt 2006; Plouffe et al. 2011), life cycle design and management (Keoleian and Menerey 1994; Westkamper et al. 2000; Ny et al. 2006), and most recently PSS thinking (Roy 2000; Tukker 2004; Bey and McAloone 2006). In addition to maximizing value, sustainability-related issues are being driven by specific regulations, e.g. "Extended Producer Responsibility" (EPR) and "Registration, Evaluation, Authorisation and Restriction of Chemical substances" (REACH), as well as more general efforts undertaken by some government or industry associations, e.g. reducing carbon emissions. Social issues are increasingly being included in addition to environmental issues under the umbrella of sustainability (Hutchins and Sutherland 2008; Missimer et al. 2010).

For the manufacturing firm, the question of whether to pursue sustainable PSS ultimately comes down to the business case: if sustainable PSS provide opportunities for involved organizations (collaborating providers, customers, etc.) to increase customer value, revenue, and preferably also reduce costs, then such solutions are likely to be considered.

Much has been written about the potential for "sustainable PSS". This article aims to explore why "sustainable PSS" have not been more widely implemented and to suggest introductory ideas for how it could be. The relationship between servitization and sustainability is also considered. The article is organized as follows. The next section describes the research methods used. The third section presents related literature. The fourth presents two case studies. The fifth section shares results. The sixth section discusses the results and relates them to the broader context of "sustainable PSS". Finally, a conclusion concisely summarizes the key findings and implications of this research.

2 Methods

This research is based on a review of related literature together with industrial case studies in manufacturing firms (Eisenhardt 1989, Yin 2002). The empirical basis for this work is case studies of business opportunities and business model transitions towards larger service content for companies and their different solutions (offerings), where tools and methods to support sustainability in product development and PSS design are in focus. Data were collected during 2009–2012 through semi-structured interviews with company managers and product developers, workshops, company visits, and by reading general company information on the companies' web sites as well as brochures and the like.

3 Related Literature

Many have suggested that PSS is able to enhance competitiveness and to foster sustainability at the same time (e.g. Mont 2002; Tukker 2004). PSS business models enable the enhancement of value and competitiveness by enabling customized solutions tailored to individual customer's needs enabled by closer and cooperative relationship between the PSS provider(s) and customers. This enhances customer loyalty, and through these relationships supports more rapid innovation since the PSS providing firm(s) are more closely connected to their customers' needs (Tukker 2004). In addition, the possibility to minimize life cycle costs per delivered functional unit are further expected to increase value by reducing the number of products required to deliver a result, reducing consumables required during operation of the product, and benefitting from knowledge utilization e.g. regarding optimal use of the product (Goedkoop 1999; Manzini and Vezzoli 2001; Tukker 2004).

Three categories of PSS have appeared in literature as early as 1993 (Mont 2000, citing Hockerts et al. 1993) and are commonly proposed in the literature (Tukker 2004):

1. Product-oriented, with a focus on selling the product with some added services;
2. Use-oriented, where use of the product is the basis for revenue to the PSS provider; and
3. Result-oriented, where the results of a product are the basis for revenue.

They are illustrated as a product-service continuum shown in Figure 1.

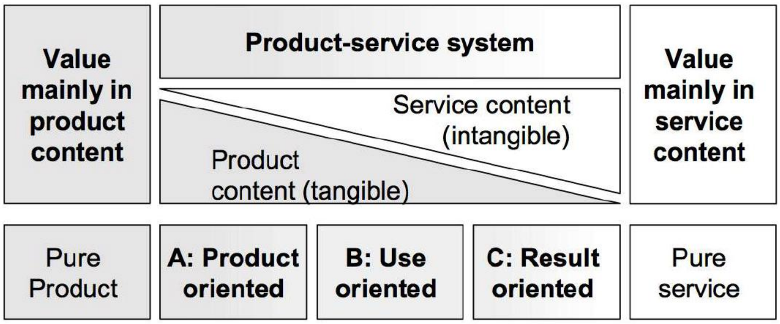

Figure 1: Three categories of PSS, adapted from Tukker (2004)

3.1 Servitization by Manufacturing Companies

At an abstract and theoretical level, rationale for a movement into services fall into one of three categories of opportunities: financial, marketing, and strategic (Mathe and Shapiro 1993; Gebauer and Friedli 2005). Servitization is seen by many as one of the best ways of manufacturing firms in developed economies addressing the five forces (Porter 1980) that influence an industry's dynamics and its profitability (Porter and Ketels 2003). It is for these reasons that management literature generally recommends moving from pure product manufacturing to at least some degree of servitization (Wise and Baumgartner 1999). Practically, if current costs can be reduced or avoided – this is a good driver. If current revenue can be increased or anticipated costs can be decreased – these are also (slightly less) good drivers. Promises for increased future revenue are not as good drivers.

The idea of services as activities has recently changed within the service management field. Grönroos (2011) answered the question 'what is service?' (note: not what is a service?): "*Service is to facilitate and support another party's practices (processes, activities; physical, mental) in a way that helps this other party achieve its goals in life or business*". By replacing the word "service" with "providing value", the product-service innovation perspective can be discerned. The idea of acknowledging the integration of the elements of products and services to sustain innovative and new solutions based on people's basic and universal needs is at the center of this perspective. Thus, such perspective puts people/users/customers in a focal position (Ericson et al. 2012). One engineering practice that aligns with this approach is Design Thinking (Brown 2008).

At the same time, similar thinking must be matched by the customer and provide an opportunity for reduced cost or increased profitability. Once there is a match – there is a candidate situation to explore PSS. However, few companies possess the knowledge and capability to actually assess value (Anderson and Narus 1998) and, by consequence, gain an equitable economic return for the value delivered to customers. This problem is further exacerbated when the product grows in complexity and when the development activity moves from a "system" to a "sub-system" or even a "component" perspective. The concept of "value" radically changes the way decisions are taken at all the levels of detail during the design activity. The optimal design solution is no longer merely found at the intersection of "performance" and "functionality", rather a third dimension is introduced that encompasses the "life cycle option" perspective. The adoption of a life cycle value creation perspective allows designers to judge different alternatives considering a more complete information set that could lead to choices based more on value-orientation over the life cycle (Bertoni et al. 2011).

As the responsibility (following warranties, legislation, material management, etc.) for the product through-life becomes more pronounced and sophisticated, there is stronger rationale to increase engagement (instead of only selling spare parts – typically a profitable part of manufacturing business today). Monitoring the product during use allows for leveraging maintenance contracts and optimizing the frequency of service intervals to e.g. minimize maintenance costs or reduce the likelihood of unplanned maintenance. Also, as seen especially amongst "new" – often "low cost" – airlines, there is an increased focus on their service and a strong effort to avoid costs associated with the aircraft and the aircraft engines. This opens market opportunities for manufacturers to better provide PSS concepts.

Several potential benefits of complementing products with services have been identified: (Lockett et al. 2011; Mathieu 2001; Wise and Baumgartner 1999; Mathe and Shapiro 1993):

- More stable revenue stream because of decreased variability and volatility of cash flows throughout the life of a product;
- Increase of revenues, as services tend to have higher profit margins and can provide a stable and countercyclical source of revenues; and
- A vehicle through which to differentiate from competition in markets that are increasingly characterized by commoditized technologies and products.

In many cases, a move to services is an attempt to access a larger share of the revenues related to operating products. Personal computers and cars, e.g. have annual expenditures on the order of five times the product costs, while larger industrial goods may be much higher, e.g. locomotives where annual costs are on the order of twenty times the purchase cost of the product (Wise and Baumgartner 1999). If the manufacturer provides and guarantees function instead of product, it lies in the interest of the manufacturer for the equipment to be used as efficiently as possible. If ownership stays with the manufacturer, maintenance and repair imply costs for the manufacturer, instead of representing the possibility of additional sales (Alonso-Rasgado et al. 2004, Brännström 2004, Isaksson et al. 2009). Overall, a manufacturing firm's interests in service are mainly based on the continuous endeavor to create or capture new sources of value for the firm.

Many case studies have been written that describe specific instances of manufacturing companies moving into services. Baines et al. (2007) list seven cases with a moderate level of detail. Mont (2004) lists more than 30 cases of manufacturing-oriented companies pursuing PSS. Goedkoop et al. (1999) list over 150 examples of PSS. In the Journal of Cleaner Production, proceedings from PSS-related conferences, e.g. the annual CIRP IPS2 - Industrial Product Service Systems conference, and similar sources, numerous individual case studies of companies adding services to their solutions can be found. Noting the lack of scale or range presented through only case studies, Neely (2007) used the OSIRIS database to explore service offerings by manufacturing firms from 23 countries, to conclude that, in 2007, of the 10,827 firms with over 100 employees and identified as manufacturing based on their SIC code, 29.52% of them offer a combination of manufacturing and service. An updated study by the same author in 2011 found 13,775 firms meeting the same criteria, with 30.10% offering services (Neely et al. 2011).

Neely's findings lend credibility to Vandermerwe and Rada (1988), who claim "*servitization is happening in almost all industries on a global scale. Swept up by the forces of deregulation, technology, globalization and fierce competitive pressure, both service companies and manufacturers are moving more dramatically into services*." Schmenner (2009) is skeptical that the integration of services with manufacturing is new to this era, claiming that manufacturers were pursuing services as a way to get closer to customers in the latter half of the nineteenth century, and suggesting that the completion of transportation (railroad) and communication (telegraph) networks set the stage for USA-wide control of sales, repair, financing, and purchasing activities by manufacturing firms. The technology change that Schmenner credits for servitization in the late 1800s may have parallels with the rapid advancement of information technology more recently, which has played a key part in enabling the full-scale integration of products, services, and technologies (Badawy 2009; Borés et al. 2003). This means that technology is no longer applied only into a single product or service, but significantly shapes the area of intersection between products and services (Auernhammer and Stabe 2002) and acts as an important mediator for product–service integration (Geum et al. 2011).

3.2 Challenges with Servitization

Despite the potential of services to contribute to manufacturing firm success, there are still challenges. Movement into services has not always provided the expected success (Baveja 2004; Gebauer et al. 2005; Neely 2008). Firms considering a move towards services need to be prepared to address the following challenges:

- Economic and business management challenges related to the risks and internalization of costs for service and maintenance (Ritzén and Ölundh 2002) and incurrence of higher costs without achievement of the expected returns (Gebauer et al 2005; Neely 2009).

- The transition into services because "goods-dominant" logic is fundamentally different than "service-dominant" logic. Manufacturer's transaction-oriented business philosophy does not support service offerings, so services cannot simply be added on top of goods-dominant logic; managing this transition requires changes in the company culture (Ritzén and Ölundh 2002; Brax 2005; Lusch and Vargo 2006; Martinez et al. 2010; Smith et al. 2012).

- Customer-related challenges such as the need for new communication patterns and new relationships with the customers (Ritzén and Ölundh 2002; Brax 2005; Isaksson et al. 2009); and marketing, e.g. motivating customers to the co-production that services require (Brax 2005).
- Product design and development, e.g. services may need to be adapted to fit customer cultures and fit customer goals (Brax 2005), and how product development integrates service developers and traditional product developers (Isaksson et al. 2009).
- Production and delivery, e.g. both an integrative information system and good information management practices are fundamental to providing complex industrial services (Brax 2005; Martinez et al. 2010). Collaboration with partners needed to provide the PSS must often be more integrated than traditional supplier-producer relationships in manufacturing firms (Pawar et al. 2009; Martinez et al. 2010).

Furthermore, the economics of servitization are debated (Neely et al. 2008; Neely 2012). For example, Visnjic and Van Looy (2009) argue that there is compelling evidence of the [economic] benefits, often based on in-depth studies of a specific firm. Fang et al. (2008) suggest that firms will fail to reap the benefits from servitization until the firms reach a certain (minimum) level of service revenue. Gebauer et al. (2005) identify a "servitization paradox" in which firms invest in servitization, but do not see the expected returns on those investments because servitization has both a behavioral and an organizational dimension, and that managers are often unprepared for the complexity, preventing those expected returns from actually happening. In fact, a Bain & Company survey revealed that only 21% of the sampled companies have experienced a real success with their service strategy (Baveja et al. 2004).

3.3 Sustainability

Generally the environmental state of practice in product development is to focus on using less materials, energy, and toxic substances. There have been calls for "factor X" reductions in material and energy use, where 'X' is some number between 4 and 50 (von Weizsäcker et al. 1998; Reijnders 1998). "Eco-efficiency" and "dematerialization" are related concepts. The "use less" mantra has strong connections with cost, i.e. using less materials, energy, and toxic materials will result in lower production, operating, or disposal costs.

The concept of "decoupling" economic growth from environmental resource use underlies much thinking with regard to the potential for a "service economy" to be more sustainable (Stahel 1997). Often possible "rebound effects" are a concern, where a reduction in e.g. material-per-unit results in an increased number of units, thus overriding any potential absolute gains (Greening et al. 2000; Binswanger 2001). While many common operational approaches to sustainability also include economic aspects (e.g. "Triple Bottom Line"), this has some problems with regard to sustainability. Either it refers to the macro economy, which is a human construct, belongs to the social system, and is designed to reach other goals e.g. social and ecological sustainability. Or it refers to microeconomic aspects, e.g. of a firm, that is concerned with maintaining its own financial goodstanding. Just as PSS approaches are stretching the traditional bounds of product development, so rigorous thinking with regard to sustainability stretches the bounds of what has become common thinking with regard to sustainability. Between the lack of a clear goal and the possibility of a rebound effect, it becomes clear that an alternative approach to sustainability could be helpful.

One such alternative approach is provided by a framework for strategic sustainable development (FSSD), which can help to clarify the concept of sustainability – both what is to be sustained, and what is required to sustain it – and to provide guidance when planning towards a sustainable human society (Holmberg 1995; Broman et al. 2000; Robèrt et al. 2002; Ny et al. 2006; Missimer et al. 2010). This is returned to in more depth later.

PSS are often claimed to contribute to sustainability, primarily by supporting such a reduction in materials and energy use (Goedkoop 1999; Tukker 2004). In this view, PSS can be a practical way to start moving towards sustainability for a few reasons, e.g.:

- The possibility for reduced material and energy use, i.e. eco-efficiency, through e.g. reduced production due to higher intensity and more optimal use of products (Wong 2004, Tukker et al. 2006, Vezzoli and Manzini 2008).
- Revenue base for manufacturing firms can shift to reward longer-lasting products instead of products that require replacement or replacement parts, which in many cases today is a significant source of revenue for those firms (Isaksson et al. 2009).
- PSS can support more rapid substitution (e.g. of products, materials, or ways or working) when new technology or new knowledge becomes available, especially in use- and result-oriented PSS in which ownership is not transferred to end-users (Wong 2001, Tukker et al. 2006, Vezzoli and Manzini 2008).
- The pursuit of "eco-effectiveness" through closed material loops is significant because it is the life cycle management of materials that is critical to sustainability (Graedel and Allenby 1998; Ny et al. 2006).

Tukker (2004) describes how different types of PSS may be significant with regard to their potential contribution to sustainability. Product-oriented PSS, e.g. may have the ability to contribute with marginal reductions in negative environmental impacts, due to e.g. more optimal use of the product. Use-oriented PSS may range from having increased environmental impact, e.g. leasing systems where users are not incentivized to operate efficiently, to "considerable reduction", e.g. product pooling systems where products that have very low utilization rates are shared and therefore far fewer of them need to be produced. Examples of the latter include power tools, carpet cleaning machines, and washing machines. Result-oriented PSS are the category put forth as having the most potential to reduce environmental impacts due to the possibility of designing a need fulfillment system that takes final consumer needs (rather than the product fulfilling the need) as a starting point.

Acknowledging the agreed upon, but not-yet-demonstrated, potential for PSS to contribute to sustainability, Tukker and Tischner (2006), writing about future directions for PSS research, state: *"[h]aving and depicting sustainable PSS-dreams in themselves will not save the earth. Understanding what it takes to realise such dreams will, and that is where our community should focus on.*"

To summarize the literature, it can be said that PSS (to varying degrees and within different types) is happening and has been happening for some time, though there are many challenges for a manufacturing firm to overcome in order to successfully implement a service strategy. However, the sustainability potential of PSS has not been fulfilled. In the next section the sustainability aspect of PSS is explored via research cases.

3.4 Cases

The two cases presented here are related research projects that have been ongoing with relationship to PSS and sustainability. The authors are directly involved in these cases.

Case 1: Aura Light Long-life Light Tubes

Aura Light International AB (Aura) produces long-life fluorescent light tubes with a life length that is approximately four times longer than the industry average. Like many firms, Aura is increasingly aware of the opportunities and risks being presented by an increasingly sustainability-driven market. Their long-life products have what can be considered an inherent sustainability-friendly attribute due to requiring a lower number of light tubes to provide the same function as a larger number of average light tubes. However, due to the long-life nature of Aura's product, there are challenges when competing with producers of "standard" life length light tubes, i.e. Aura has one-fourth as many opportunities to generate revenue from the sales of a physical product as its competitors. From a sustainability perspective, the long-life product is obviously worth exploring since it reduces material flows by approximately one-fourth due to requiring one-fourth as many light tubes to provide light for the same number of hours. Still, electricity used to power the light-tubes is by far the most significant (financial) cost. The electricity is also a primary source of environmental impact during the light-tube's life cycle, depending upon the source of electricity. Further, because it contains small amount of mercury, the way in which the light tube is handled at the end of its life is critical from a sustainability perspective.

A study presented by Thompson et al. (2010) considers the opportunity for Aura to "sell light" from three different perspectives: the economic perspective of the light customer, the economic perspective of the light producer (Aura), and a sustainability perspective. One key in the potential success of moving to a PSS-based offer is the opportunity to capture as value the reduced costs from not having to change out the light tube three times when compared to competing light tubes. A further benefit is the technical loop that becomes possible, supporting the likelihood that light tubes are handled properly at the end of their useful life.

There seem to be possibilities for "win-win" situations for both the customer and the provider, yet this has not yet happened. It can be noted that the light tubes are part of a relatively simple supply chain that has not had a need for deep collaboration in order to do product development. There has been significant research into how to make light tubes last longer, how to handle light tubes at the end of their useful life in order to deal with especially the mercury, and also to some extent the colors of light and how that affects customers. There has not been much exploration of how products might be co-developed with customers or other value chain actors. Neither is there an extensive capacity for the company to provide use-related services that might be required to guarantee light performance. A major point is the customer procurement processes, which typically consider lighting to be a capital (rather than operating) expense.

Case 2: GKN Aerospace Engine Systems, Engines, and Components

GKN Aerospace Engine Systems is a company providing components and sub structures to the commercial aircraft business and also providing solutions as an OEM for the Swedish Air Force through providing the engine to the Gripen aircraft. Products in this industry frequently have quite long product life cycles, i.e. 30-50 years, and partners are keen on knowing life cycle costs upfront. The industry is also generally accustomed to working with engineering performance.

Changes in the industry are being driven by demand to reduce life cycle costs. The aerospace industry also has goals to reduce contribution to CO2 emissions, which is seen as highly aligned with the drive to reduce life cycle costs. Aircraft engines are expected to become larger in diameter to increase the bypass flow, thus reducing fuel consumption (a major cost and sustainability driver) and obtaining other desirable effects. Engines are also expected to support a "More Electrical Engine" concept (Provost 2002), an innovative architecture that aims to replace electric hydraulic and pneumatic systems with one single, globally-optimized, electrical system, enabling the proper integration of propulsion and secondary power into the airframe. In light of these trends, it becomes less intuitive for an engine sub-system manufacturer to understand which component/technology might offer the highest value contribution in 10, 20 or 50 years. Considering, e.g. the development of an innovative engine intermediate case technology (IMC) engineers and designers must be aware, early on, of the impact of their design choices in a lifecycle perspective, and have the ability to deal with this using simulations (Isaksson et al. 2012).

As one example, the company recently started to offer a service (Life Tracking System - LTS) that combines deep product knowledge with advanced in-service data analysis to provide maintenance planning and scheduling services (Wallin 2012). Advanced "life cycle simulations" of critical parts can be combined with analysis of field measurement. This analysis cannot be made without the deep knowledge residing within the company as a manufacturer. The win from a sustainability point of view is more optimal use of material and resources; the win from a flight safety point of view is increased reliability and availability of the aircraft system, etc.

The benefit must be clear from both the operator and user of the aircraft, the manufacturer and in this case the supplier. In general – the LTS PSS solution can be used together with sales of entire aircrafts and engines as a means to optimize and measure the state of the system over its lifetime. In this way it follows the basic "trend" of integrating the through-life perspective.

3.5 Problems of Getting to "Sustainable PSS"

Through the literature review and research behind the two cases presented, two overarching problems to implementing "sustainable PSS" are identified.

First is the set of day-to-day challenges that companies currently face as they try to implement PSS. These challenges are related to the implementation of solutions that are function-oriented and co-developed. Co-development here means simultaneous development of the product and the service to arrive at a PSS. This, in turn, requires closer collaboration between the PSS provider(s) and customers. The "PSS provider" here likely includes the manufacturer, but may not be limited to only the manufacturer, because (new) capacity for service delivery is also often needed. This can be obtained in-house through significant organizational change, or by bringing in new partners. Often, the sheer size of these required changes (e.g. business models, competence, organizations, tools, legislation, marketing, procurement practices, value chain) means that it can be expected to take some time to get implemented.

The second aspect of getting to "sustainable PSS" is bringing in the sustainability aspect. While PSS literature frequently discusses the potential to reduce materials and energy use, there are two problems here. First, improvements with regard to sustainability is not guaranteed by PSS; there are many ways in which PSS can lead to overall less sustainable solutions, e.g. the "rebound effect." Second, the general understanding of sustainability in the PSS literature is not sufficient to achieve sustainability. Even though large, i.e. factor 20, reductions in use of materials and energy could go a long ways to reduce pressure on ecological systems, such reductions still leave a gap to global socio-ecological sustainability.

These are discussed in more detail in the following section.

4 Discussion

4.1 Changing "Solution" from Physical Instantiation to Function

With the first problem, one key is the change from a focus on the physical instantiation (an artefact) to the desired function, e.g. moving from a focus on selling light tubes to lux or from a jet engine to power. This enables a start at finding efficiency improvements that can lead to more optimal use or performance of the products needed to provide the function, thus reducing life cycle costs.

This concept is not new, but may require a return to the roots of PSS literature, where there is heavy emphasis on "function fulfillment" (e.g. Goedkoop 1999). Services have been added to products by manufacturing firms for years (Schmenner 2009; Vandermerwe and Rada 1988). As servitization literature has been brought into the PSS arena, some focus on this "function first" aspect has been lost. Yet PSS was introduced as a concept distinct from servitization because it had something new to offer. The new aspect of PSS may have been minimized because manufacturing firms are motivated by the possibility to increase and make more consistent revenue streams through services, but have too much invested in current technologies (hardware, infrastructure, knowledge, etc.) for significant changes to the product to be economically viable.

The two case studies described earlier have proposed to add or have added services to existing products as shown in Figure 2. This is what appears to be a PSS solution of the product-oriented type, i.e. the sale of a product is the main way in which value is exchanged, and services are added as a "wrapper" to the product. However, the intent with PSS is to reconsider the combination of products and services in order to find combinations that best meet customer requirements. To achieve the optimization that PSS seeks, the function would ideally be the starting point of a design process, thus enabling identification of the optimum combination of products and services that meet the desired function. That is, a PSS is first designed as a system with that system-level solution leading to the design of combinations of products and services that jointly provide value. The various definitions in literature do not always provide clarity on this (e.g. Mont 2002, Baines et al. 2007), though most contributors refer to the somewhat ambiguous definition from Goedkoop (1999) to say PSS are "product(s) and service(s) combined in a system to deliver required user functionality in a way that reduces the impact on the environment." However, Roy clarifies with the sustainability aspect (emphasis added):

> *The key to sustainable product-service systems is that they are* ***designed*** *and marketed to provide customers with a particular result or function…Moreover, thinking in terms of* ***designing a system*** *to provide a function* ***rather than***

> ***designing a product*** *quickly shows that there are often many alternative ways of providing that function.*
> (Roy 2000)

Tukker, in agreement with Roy and writing from a perspective that emphasizes the sustainability potential of PSS, concludes (emphasis added):

> *… in theoretical terms it is easy enough to define a functional result at a high level of abstraction (e.g. a person that needs transport from A to B), and then to conclude that systems can be designed that can deliver this function a factor of 4–10 times more efficiently than the currently dominant product system, i.e. transport by own car.* ***However, it does not work the other way around.***
> (Tukker 2004)

Thus, first designing at the product-service system level is critical to designing a "sustainable PSS", as shown in Figure 3. This is very challenging when starting already with the existing product, since the answer to "which product?" is already decided. However, it could be possible that manufacturing companies, through adding services to existing products, develop the competence and capacity required in order to deliver services. As the service competence and capacity become more mature, the next major development step could be innovation at the product-service system level.

4.2 Changing System Levels

The previous section described the need for a shift in thinking from developing/selling an artefact to developing/selling the function the artefact provides. Consideration of different system levels is another key aspect of the problem relating to implementation of sustainable PSS. A major shift in solution space can occur when the system level in focus changes to a broader or higher system level. The function of a jet engine is to provide power to move an aircraft; the function of the aircraft is to move people and goods; people and goods want/need to move because they are not where they can interact/experience/be consumed. The function at each of these levels can be considered. Figure 4 illustrates different system levels in the aerospace value chain.

If power for an aircraft is the function in focus, what is the ideal combination of products and services to provide this? The jet engine value chain is more broadly considering alternative concepts that have the potential to lower operating costs, e.g. advanced turbofan, geared turbofan, and open-rotor. There are technical and other challenges relating to these alternative concepts. They may have significantly different through-life value implications for the manufacturing firms. Some

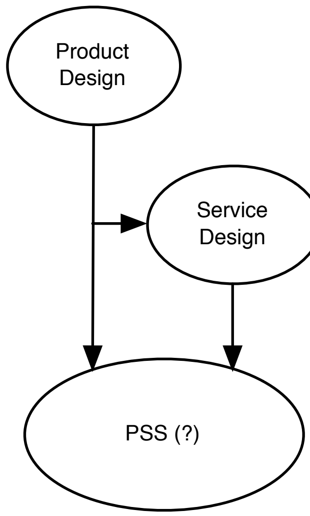

Figure 2: Servitization undertaken by manufacturing firms keeps existing products and adds services. This can be considered product-oriented PSS, but they miss the opportunity to reconsider how to best deliver functional results.

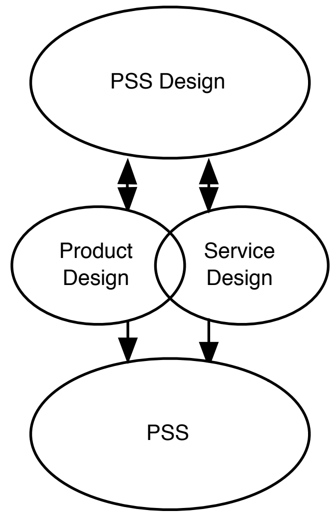

Figure 3: PSS intended to support sustainability needs to consider possible solutions first, and then lead into the products and services that enable those PSS solutions to be delivered.

concepts may essentially be "plug and fly" while other concepts may require structural changes to the aircraft; such changes significantly alter the through-life value equation. While these factors are primarily "internal" to the jet engine value chain, "external" factors are also contributing to significant changes in the value equation: energy prices and availability, regulations are evolving (e.g. carbon reduction targets), materials are developing (e.g. carbon-fiber composites), and multiple tiers of customer demands are changing (i.e. airlines as customer of the jet engine manufacturer, and flying passengers as customers of the airline).

If the movement of people and goods over long distances is the function to be considered, what is the ideal combination of products and services to provide this? As the global context changes, do alternative combinations begin to have more attractive value equations? As energy prices increase, do alternative transport modes that today are implausible, e.g. inter-continental magnetic levitation trains operating in vacuum tubes, become options worthy of consideration? Does rapidly developing IT capability and capacity make video conferencing a more viable substitute for face-to-face meetings, reducing the need for passenger transport?

This question of system level is traditionally a strategic focus for a company, more than an engineering challenge. Oil companies rebrand themselves as energy companies; truck manufacturers become transportation solution providers; forklift manufacturers instead provide warehouse transportation solutions. However, as PSS approaches expand the boundaries of what is considered during product development, these broader system levels also influence product development.

Figure 4: Multiple system levels in an aircraft (Adapted from Isaksson et al. 2012).

Similar opportunities exist with the case of light tubes: if on the order of 90% of the total life cycle cost of a light tube is the electricity used to power it, of course it is rational to make improvements that reduce power consumption. But why not also consider alternatives to the fluorescent light tube? At the same functional level (artificial light powered by electricity), LEDs are viable competitors, though have economic and strategic risks of their own, e.g. availability of materials and toxicity of components. At a higher functional level (illumination of space), better utilization of daylight can, during some hours of the day, lead to reduced need for electricity. Here there may still be a need for providing artificial light during hours when daylight is insufficient; a PSS can include both a product that enables sunlight to travel from outside buildings to interior meeting rooms and the fluorescent light tubes, together with the services that enable the optimal combination of each from both the user's comfort and the economic perspective.

However, implementing such a PSS solution dramatically increases the complexity of doing business. More actors are involved and more technical systems need to be linked. Physical artefacts (still) need to be developed, and possibly more of them (e.g. structures to distribute light to interior rooms in a building). It becomes (more) necessary to consider lighting solutions when structures are designed and built, instead of adding lights as needed after the structure is in place. Business models need to be changed: reductions in electricity lead to cost savings for customers, but not necessarily for manufacturers. And in current business models where revenue is tied to sales of physical artefacts, replacing artificial light with daylight reduces the number of light tubes sold, and thus the manufacturer's revenues. This is not a win-win, so it is a no-go.

To product developers and engineers and business managers, the idea of changing system levels is daunting. It is disruptive, and it challenges existing ways of working in very significant ways, many of which were introduced in Section 3.2.

4.3 Market demand and Co-Development as Enabling Factors

PSS solutions by definition imply an agreed solution between the provider and the customer. Any new solution that requires modification or change compared to established practice and relations needs to be co-evolved among both the customer and the provider(s), i.e. the manufacturer(s) and possible additional service-providing partners. A major motivating factor, therefore, determining whether or not manufacturing firms pursue PSS may be the extent to which customers demand PSS. In order to be able to consider alternative ways or providing light, Aura may need to engage more closely with customers to better understand customer needs and to further develop relationships with key customers that allow Aura more insight into customer practices. This may not necessarily be related directly to the technology as such, but may also be related to the customer's procurement practices that have evolved over time to the point at which capital goods are dealt with separately from operating expenses. GKN, working with products that have very high performance requirements, and thus sophisticated design and development aspects, has needed to have tight integration with its customers particularly in the commercial market where it is not the OEM. These established relationships contribute to the ability to advocate for providing services.

The goal of the manufacturing company is to find the ideal point on the product-service continuum (Figure 1) that fits the firm's unique situation and enables it to add value to customers through reducing costs and increasing benefits. This depends largely on the company's current situation including knowledge, production capacity, service delivery capability, etc. This does not specify sales being based on product, use of product or functional result. Rather, the basis of sales should be whatever combination of products and services offers the most value, i.e. is preferred by the firm together with the customer. This could be any of the categories of PSS identified by Tukker (2006): product-oriented (revenue from transfer of ownership of the product), use-oriented (revenue based on use of the product), or result-oriented (revenue based on result facilitated by the product). Practically, however, as manufacturing firms enter into PSS, they by necessity start with product-oriented PSS because the firm is as it is, i.e. it has the resources and capacities that it does (production capacity, knowledge, relationships, etc.) and cannot make large and instantaneous changes. The customer, when entering into PSS, may also have established conditions and practices that limit the ability to make rapid changes.

An important note: It is no small task for a manufacturing firm to arrive on the PSS continuum. Much research and experimentation are going into this – entire new disciplines (e.g. service engineering) are evolving to support this initiative, and companies are spending decades developing the knowledge management capabilities and service delivery capacity. Still, with the objective of "sustainable PSS", only getting to PSS is not enough.

4.4 Sustainability in "Sustainable PSS"

Previous sections have discussed the complexity of PSS, without a specific focus on sustainability aspects of PSS. In order to discuss "sustainable PSS", the concept of sustainability needs to be clarified due to many conflicting and non-operational definitions that exist (Johnston et al. 2007; Glavic and Lukman 2007). Often, especially in PSS literature, sustainability is considered in a relative sense, i.e. how much better a new version of a product or PSS is than a previous version. This leads to, e.g. "factor X" efforts to reduce known environmental impacts. At the broadest (relevant) system level, however, sustainability discussions should be based on sustaining human society (the social system) and the global ecological systems that the social system depends upon. A discussion on sustainability thus becomes absolute (what is necessary for a sustainable society) rather than relative (how much better this product is relative to a previous version of this product).

Taking the broader focus on what is necessary for a sustainable society (and the ecological systems society depends upon), it is necessary to clarify what it means for society to be sustained. The success level of the framework for strategic sustainable development (FSSD) reasons that as long as something is not systematically contributing to the degradation of the global social and ecological system(s) that are to be sustained (directly, or indirectly through dependence upon some other thing), then that thing can be considered sustainable. Conditions for a sustainable society are then articulated in the form of first-order principles that describe the boundary conditions for a sustainable society in a way that strives to be necessary and sufficient, as well as general, concrete, and non-overlapping. The ecological system can be destroyed by systematically changing the chemical composition of the ecological system, or by systematic physical degradation of the ecological system. Thus to be sustained, the ecological system should not be subjected to systematically increasing (for references, see Ny et al. 2006):

1. Concentrations of substances extracted from the Earth's crust,
2. Concentrations of substances produced by society, or
3. Degradation by physical means.

Describing social sustainability with the same reasoning, however, is more challenging, and work is currently underway to better understand how constraints for a sustainable social system could be expressed along similar lines as the ecological system constraints (Missimer et al. 2010). An early attempt at boundary conditions for the social system is (for references, see Ny et al. 2006):

4. People are not subject to conditions that systematically undermine their capacity to meet their needs.

This approach to defining sustainability by setting boundary conditions for a sustainable society enables freedom in design space. This freedom supports both function-oriented development and expanded system boundaries because the design challenge is now framed by looking forward into a solution space bounded by sustainability constraints instead of being constrained to making improvements on an existing product concept. FSSD literature refers to this as "backcasting from principles" (Holmberg and Robèrt 2000; Broman et al. 2000; Ny et al. 2006). Furthermore, in realization that products and service today are contributing to violations of these principles and cannot immediately change, guidelines are provided for how to select and prioritize actions that navigate towards those boundaries in a strategic way (for references, see Ny et al. 2006).

To work towards sustainable PSS, it can be helpful to think about sustainability with regard to the components of the PSS both individually and collectively. Whether product design happens before (Figure 2) or after PSS design (Figure 3), the development of the physical products is a critical point at which to include sustainability thinking. This is illustrated in Figures 5 and 6 with the addition of "Sus 1". An approach for integrating a strategic sustainable development perspective in conceptual design that is applicable here is presented by Thompson et al. (2012) that intends to address some of the challenges in making the SSD approach operational in a product development context. While sustainability aspects of a product cannot be considered without also considering the life cycle of the product, the approach presented by Thompson et al. (2012) has a product-centric viewpoint.

PSS provides the opportunity to better consider the life cycle management of those artefacts. This is consistent with the function-oriented perspective earlier deemed critical to PSS development, i.e. first considering sustainability at the PSS level also becomes critical to arriving at sustainable PSS. Thus, as shown in Figure 6, sustainability should be considered when designing at the PSS system level, e.g. to find ways to decouple firm revenue from sales of products, to consider and address potential rebound effects, to support products being contained in technical loops, etc.

Sustainability aspects still need to be considered at product-level design, i.e. as the PSS solution evolves, the product(s) included can also be designed with sustainability in mind. In the example of Aura, the PSS solution might include a combination of increased use of daylight via light distribution tubes that transfer sunlight from outside to interior rooms in a building. Still, fluorescent tubes might be part of the solution in order to provide additional light when sunlight is not sufficient, and can be designed in a way that works towards compliance with sustainability principles. A critical point here: the SSD approach emphasizes moving in the direction of operating within the boundaries of a sustainable society through economically viable steps, as opposed to trying to become sustainable in that sense immediately at any cost or risk.

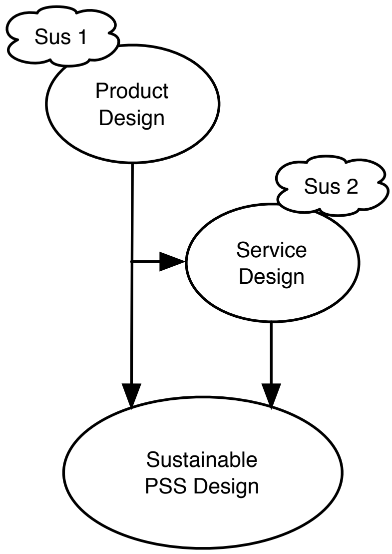

Figure 5: Adding sustainability considerations into the current situation.

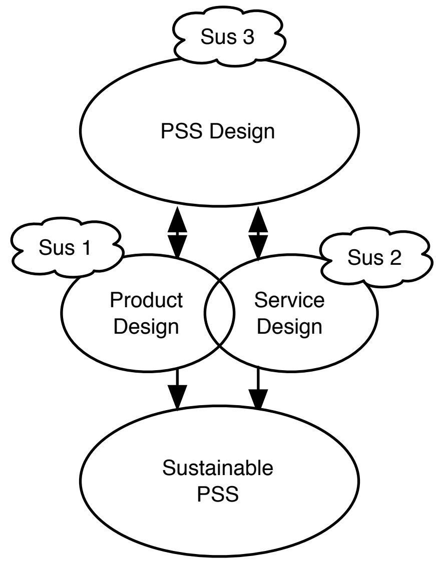

Figure 6: Adding sustainability into a PSS design situation where PSS level is designed first.

4.5 Moving Forward with Sustainable PSS

As manufacturing firms add services around their existing products, they gain competence in developing services and understanding of the capacity issues related to delivering those services. With this increased service competence and capacity, contracts that move towards payment being based on functional results can be written more confidently. This, in turn, incentivizes PSS-providing firms to minimize through-life costs.

The Aura case is still in the early stages of considering adding services. Thompson et al. (2010) present rationale for how to make an innovation in how the company communicates their offer, moving from the sales of light tubes to selling the function of light. This supports communicating and possibly capturing value that is enabled through the long-life attribute of their product by reducing costs associated with swapping out the competitor's light tubes. Possible future moves for Aura could be that as this progression occurs and Aura gains confidence in their ability to understand their customer's needs, Aura could write agreements with customers that include providing a certain quality of light when it is needed. If Aura is able to bring the electricity costs (estimated by Thompson et al. (2010) to be on the order of 90% of the cost for lighting) into the domain of their responsibility, then they have incentive to redesign lighting solutions in their customers' facilities that could include e.g. replacing electricity use during daylight hours with passive solar lighting, enabling them to replace high-cost, high-environmental-impact electricity with low-cost, sustainable sunlight. Building the organizational capacity to deliver lighting-based solutions is not simple, and there are many related strategic questions for the company.

Strategic questions are common in PSS pursuits, and viable solutions are context dependent, making it difficult to provide general suggestions. What is clear, however, is that the pressure on business to perform in the short-term often restricts pursuit of more radical innovations, so incremental and evolutionary solutions often result. When sustainability-related decisions are guided by the aim for longer-term alignment with the boundary conditions for a sustainable society described by the FSSD, short-term decisions can support a strategic move towards implementation of sustainable PSS.

5 Conclusion

This article explored why "sustainable PSS" are not more widely implemented. Two overarching reasons are put forth here. First, the implementation of PSS as such, i.e. servitization, is challenging by itself. It is clear that PSS are happening; manufacturing firms are pursuing services in order to e.g. increase or stabilize revenue or to maintain competitiveness. Further effort is needed to move from today's common situation of adding services to existing products, towards designing at the PSS-level first in order that more optimal products to meet the function might be identified while being designed together with services. Also, a PSS approach encourages through-life consideration, implying a need or opportunity to reconsider the system level at which to focus on functional development. Ultimately it is market demand that enables a manufacturing firm to pursue PSS, and co-development of PSS solutions is critical given the through-life aspect.

Second, common conceptions of sustainability in the PSS research and practice communities are not sufficient to arrive at a sustainable society. Currently, many (not all) PSS support material and energy reductions, and this supports reduced life cycle costs. This is not synonymous with sustainability, though may be supportive of movement towards sustainability. A more concrete understanding of sustainability is needed in order to direct PSS towards more sustainable solutions. The framework for strategic sustainable development (FSSD) approach to describing boundary conditions for a sustainable society and providing support for innovating and selecting strategic actions towards fulfillment of these boundary conditions can provide this.

The movement towards sustainable PSS is complex and full of risk, and progress therefore appears slow as companies initially find their way in this new arena. However, manufacturing companies and their value chains are developing service competence and delivery capacity. Complementing these efforts with a more robust approach to sustainability as proposed here will further enable them to work towards implementation of sustainable PSS.

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Paper F

Introductory Approach for Sustainability Integration in Conceptual Design

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Introductory Approach for Sustainability Integration in Conceptual Design

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Abstract

This work introduces an approach for how to develop and put into use sustainability criteria in conceptual design by utilizing a set of sustainability principles as design boundaries and aligning sustainability criteria throughout each of the steps of a generic design cycle. This addresses two problems: 1) sustainability criteria are not robust enough, while sustainability principles are seldom directly applicable for use in requirements specifications, and 2) in an operative design situation, there is little or no time and data available to undertake the work to integrate sustainability.

Keywords

conceptual design, sustainable design space, sustainability criteria

1 Introduction

The introduction of sustainability-related requirements into new product development has been a popular topic since the 1990s, and one of the very roots of the topic – scarcity of resources – indicates that market forces will require improved ways of dealing with sustainability for product developing companies. The question remains, however, of the importance of considering sustainability aspects in product design, and if important - how to do it? This paper assumes importance and works to answer the question of how to do it by presenting an approach, currently under development, to include sustainabilty aspects in a generic design process by defining a sustainable design space inpsired by the early steps of a set-based concurrent engineering (SBCE) approach, and then describing how each stage of the generic design process can be aligned in order to arrive at more sustainable products. In a SBCE approach, rather than defining and evaluating design concepts, allowable design "sets" are identified and non-allowable design areas are omitted. The allowable set is determined by requirements and limitations from applicable areas [Sobek etal. 1999].

Current practices of product development in manufacturing companies are predominantly based on cost/profit models [Asiedu and Gu 1998], that aim to achieve high quality at low cost with a result of high profit. Sustainability requirements are commonly perceived as extra costs, due to e.g. generating additional design constraints that must be met or increasing testing and assessment costs. This is due partly to the way that sustainability aspects have been considered, which is often by conducting assessments after significant decisions about a product have already been decided upon. A late design change means higher costs as the degrees of freedom reduce with development time. Awareness of the limitations also from sustainability perspective earlier could instead result in new more innovative solutions. The paradigm of product development towards increasing value (and profit) by reducing costs and increasing benefits is unlikely to change. However, reconsidering how and where sustainability aspects are brought into the product development process is possible to change, to support both reducing costs and increasing benefits. See e.g. [Waage et al. 2007] for discussion; [Schmidt and Butt 2006] for an industrial example.

"To make a difference" the impact of sustainable development needs first to be understood in several dimensions. There are operative, tactical, and strategic aspects with regard to sustainable development that need to be considered when integrating sustainability in produt design. The operative aspect is that people developing products need tools and techniques to impact both the search and evaluation of product concepts within their working environment. The tactical aspect is important since it "controls" the timing of when certain objectives need to be embedded. A clear example is the effectiveness of legislative norms, agreed policies, or simply the timing of a product's introduction (and use) on the market. The strategic aspect is critical, for example, in a development organization that wants to evolve, expand and change the direction of business towards being (and being perceived as) a leader in providing sustainable solutions.

1.1 Conceptual Design

Conceptual design has been widely recognized and studied since the significant impact on nearly every aspect of the product – and its subsequent realization – are determined in this phase, with regard to both life cycle cost [Asiedu and Gu 1998], and presumably also sustainability impacts. It is characterized by many important design decisions, while the data and information is yet limited. The freedom of design is constrained and knowledge of the design problem is increased as progress is made through the development process. Here we use a simplified conceptual design process to explain current limitations and propose methods to address these limitations.

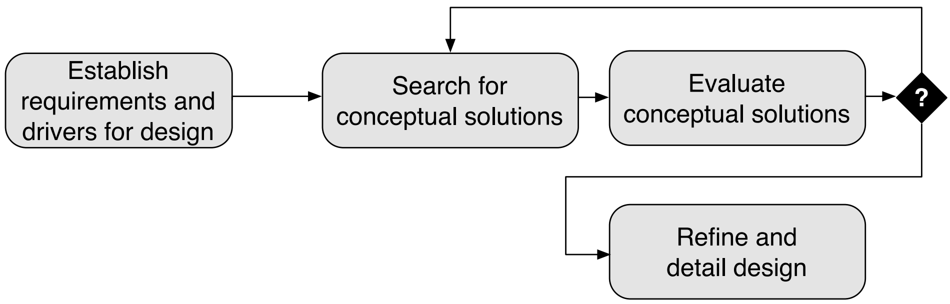

Figure 1. Simplified and generic design cycle

1.1.1 Sustainability in a Generic Design Cycle

With the generic design cycle shown in Figure 1, we can consider how sustainability criteria might today be considered in each of the steps. In the first step – establishing requirements and drivers for design – criteria need to be identified that can be used to formulate requirements for the development project. In the second step – search for conceptual solutions – the development team needs guidance and support tools to enhance the search for more sustainable solutions. This is partly realized since the criteria previously expressed as requirements are available in this step, yet the criteria alone are not sufficient. In the third step – evaluate conceptual solutions – the proposed solutions must be represented so that they can be assessed, i.e. against the sustainability requirements. Comparison against the sustainability criteria are necessary. At this stage, it is unlikely that a concept is well enough defined to allow a full analysis. However, the degree to which the concept is aligned with each of the sustainability criteria may be possible to measure (qualitatively and/or quantitatively). In essence, there is a "sustainability compliance index" per each concept. At the actual decision situation to go or not to go further with the proposed concept (?), there is a need to express the use of a "sustainability compliance index" in a way that can be balanced/judged with any other requirements to be fulfilled. Finally, the concept selected to advance for further refinement and detailing needs to capture and represent the rationale for how the selected solution must be treated for the detailing, since there are several more decisions to be made that relate to sustainability criteria fulfillment. This is in some ways different from some alternative methods and techniques, such as most Design for Environment (DfE) techniques, in which the focus lies on assessing the environmental impact of concepts and solutions, and little or no support is typically found for solution seeking and "what is good enough," i.e. targets are not set or are not operational in the designer's working environment.

1.2 Sustainability Criteria Used Today are not Sufficient

When sustainability-related criteria exist in product requirements today, they are often developed based on identifying things that are assumed to be desirable or not, along with being easy to assess. An example: minimization of energy is nearly always mentioned in regard to sustainability of products, see e.g. [Herva et al. 2011]. Generally minimizing energy use is good; however, there are forms of energy that can be utilized with no or very low sustainability-related impacts: passive solar, for example. This to say: it is not energy minimization per se that is the goal, but rather the minimization of certain types of energy that are associated with negative sustainability impacts. To address this, the basic principles for global socio-ecological sustainability put forth by [Robèrt et al. 2002] are used in this paper. These principles were arrived at by first assuming to arrive at a complete enough understanding of the global socio-ecological system so as to be able to define success for planning efforts within that system, i.e. a sustained human society, including the ecological system upon which society depends. That definition of success is delivered in the form of first-order principles that are intended to be applicable to any planning effort to arrive at the definition of success by virtue of being sufficient, necessary, concrete, generic, and non-overlapping. These sustainability principles state that in a sustainable society, nature is not subject to systematically increasing:

1. Concentrations of substances from the Earth´s crust,
2. Concentrations of substances produced by society,
3. Degradations by physical means,
   and, in that society,
4. People are not subject to conditions that systematically undermine their capacity to meet their needs.

These principles are designed for "backcasting" (i.e. imagining success in the future and then exploring strategies to reach that success) in contrast with "forecasting" (i.e. analyzing and projecting current or historical trends). We refer to "strategic sustainability" as the combination of these ideas, i.e. backcasting from sustainability principles. These sustainability principles act as system boundaries for sustainable solutions; anything within the boundaries is in essence the set of "sustainable solutions". This approach to sustainability is essentially the same as the first element (define feasible regions) of the first principle (map the design space) of

SBCE set out by [Sobek et al. 1999]. Thus, limiting the range of applicable design solutions in such way is in line with SBCE.

1.3 Strategic Sustainability in Early Phases of Product Innovation: Results from a (Previous) Descriptive Study

To understand the current situation regarding how strategic sustainability aspects are implemented in the early phases of a product innovation process, a descriptive study with a qualitative research approach was conducted at six larger product development companies in Sweden as part of the project "Decision Support for Sustainable Value Chains" (DecSus). This study investigated the current practices for how those companies currently have, and could better implement, a strategic sustainability perspective in the early stages of their product development. The scope of the study and the resources available for data collection included company documentations of the product development process and semi-structured interviews of twenty persons at the different companies with different responsibility areas, i.e. product planning, product development, project management, supplier development and environment, environmental management, advanced engineering, and environmental engineering [Hallstedt et al., in review for journal publication]. Key results from this study include the following.

Interviewees named eight potential types of sources in which sustainability requirements or input for sustainability requirements could be identified: customer requirements, company standards (e.g. material lists, supply assessment requirements), company's environmental targets (for example based on product strategies and/or environmental management system), regulations (e.g. Registration, Evaluation, Authorization and restriction of CHemicals - REACH), life cycle assessments, chemical analysis, customer analysis, European Union (EU) studies.

All the interviewees suggested that sustainability aspects should be included very early in the innovation process, in the "product planning" phase in order to have an affect on the product design. As a result of this study, the authors have argued that if the identification of sustainability aspects were to come earlier, e.g. in the product requirement list, it then would be easier to; i) reduce the negative environmental impacts; ii) avoid additional costs for assessment or late-stage redesign; iii) plan for solutions as flexible platforms towards sustainable solutions; and iv) use sustainability as a driver for product-service innovations [Hallstedt and Thompson 2011]. The importance of defining sustainability criteria and considering these as equally important as traditional requirements of cost and quality from the very beginning for successful implementation are also emphasized in e.g. [Waage 2007].

The study also identified some challenges that should be addressed to avoid suboptimization and to guide decisions towards success for the company in a sustainable society. These included: i) having a full social and ecological sustainability perspective, ii) covering all aspects of the product's life cycle, and iii) complementing the common "forecasting" approach with a "backcasting" approach (described in previous section).

The results from this descriptive study formulated some guidance for sustainability criteria development that together with theories of basic principles for global socio-ecological sustainability are used to build (in this paper) our first prescriptive approach for integrating sustainability in criteria development. Additional insight was gathered from a two-day workshop involving representatives from Volvo Aero, an airframe manufacturer working within the Volvo Aero value chain, and researchers involved in this research project. The workshop focused on how a backcasting from sustainability principles perspective could support enhanced design requirements.

2 Problem Addressed

Two related problems are addressed in this work that are related to bringing sustainability into the conceptual design process. The first problem addressed is that common sustainability criteria are not robust enough to provide a complete picture of sustainability, while sustainability principles identified by Robèrt et al. (2002) are seldom directly applicable for use in requirements specification for a new product. The second is that in an operative design situation, there is little or no time and data available to undertake the work to integrate sustainability. This was not explicitly identified in the previous study, but becomes evident as we try to conceptualize solutions to the first problem. Therefore this work is a first step to arrive at an approach for how to both develop and put into use sustainability criteria in conceptual design. The first problem is addressed by utilizing a set of previously-published sustainability constraints that match precisely with the early steps in set-based concurrent engineering, but to our knowledge have not previously been used in this context. The second problem is addressed through a proposal for how to align sustainability criteria throughout each of the steps of the generic design cycle.

3 Developing Sustainability Criteria and Aligning with Conceptual Design

This section describes a 5-step approach for how the sustainability criteria are introduced and considered throughout the design cycle. The five steps are based on a modification to the simplified conceptual design model in Figure 1: a step is added to define the "applicable" design space (box 2 in Figure 2). This alteration is a step towards adopting "Set Based" principles as described by [Sobek et al. 1999]. The subsequent search and evaluation activities serve to limit the design space while making conceptual solutions more robust and detailed until the conceptual design phase is completed. This is explained in Step 2.

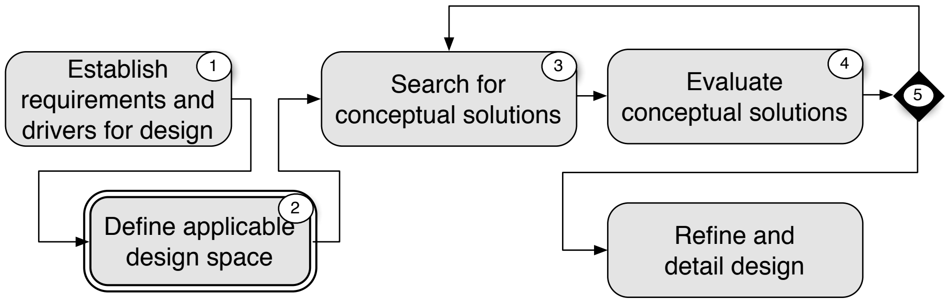

Figure 2. A strategic conceptual design cycle;
Numbers refer to steps explained below.

Step 1: Establish sustainability-based design requirements

The results from the descriptive study and theories of basic principles for global socio-ecological sustainability formulated some guidance for sustainability criteria development that together build the base for the suggested first prescriptive approach for sustainability criteria development. This process needs to: i) be simple enough to collect data and thereby possible to update regularly at the company; ii) be based on company requirements with the goal to link some sustainability criteria to technical product requirements; iii) include a full product life cycle (from resource extraction to disposal phase) and include a full socio-ecological perspective; and iv) be based on both forecasting (trend analysis) and backcasting (goal-oriented planning).

Step 1.1: Collect existing sustainability-related criteria

This step is a divergent step to identify all criteria that could possibly be used. These can come from a variety of sources, such as i) product requirements: sustainability-related criteria already exist e.g. in technical specifications for a product or previous environmental assessments of related products; ii) company requirements & goals, e.g. corporate documents and environmental policies; iii) industry requirements and goals, e.g. within the aerospace industry, the Advisory Council for Aeronautics Research in Europe (ACARE) publishes targets for e.g. future CO2 emissions; and iv) existing regulations at national and international levels, e.g. REACH.

Step 1.2: Review all product life cycle stages through sustainability principles

Since the criteria in Step 1 are typically coming from a forecasting approach based on known current problems, this step introduces a backcasting approach. Create a map of the product life cycle stages. Use this map to review each life cycle stage with an eye to each of the sustainability principles. (See related concepts from e.g. [Byggeth and Broman 2000]. Where a potential contribution to a violation of a sustainability principle is found, a new criterion can be developed and added to the list.

Step 1.3: Reduce the criteria list based on meta-criteria and relationship modelling

The goal of this step is to arrive at a manageable list of criteria that cover major sustainability aspects of the concept to be evaluated. In this step the criteria list will be shortened with the goal of balancing comprehensiveness (i.e. not being unnecessarily simplified in a reductionistic way) with the ease of use demonstrated in the Ford of Europe case where no new data requirements were made to accommodate the sustainability criteria [Schmidt and Butt 2006].

Criteria are then grouped and classified into product life cycle phases (e.g. material sourcing, production, distribution, use, end-of-life). Each criteria also has a time perspective (i.e. short term and long term) to reflect urgent requirements versus expected requirements in future. Furthermore, address similar or conflicting goals, e.g. if an industry goal is to reduce CO_2 emissions by 30% but product requirements are only sufficient to reduce CO_2 emissions by 10%.

To further shorten the criteria list, it is then scrutinized by a set of meta-criteria. It is important that these meta-criteria allow for a comprehensive socio-ecological sustainability perspective, while also ensuring that the criteria will be usable in the operational working environment. Meta-criteria suggested here are based on previous research by e.g. [Schmidt and Butt 2006] and the PROSUITE project [Dreyer et al. 2010]:

1. Applicability: Criteria must be applicable to different concepts;
2. Logic and simplicity: Criteria need an unambiguous measurement rule and measurement units;
3. Feasibility / data availability: Criteria must draw on information that is possible to obtain;
4. Clarity: Each criteria has to measure a measurable entity;
5. Relevance: Criteria must represent central aspects of the dimensions; and
6. Coverage: All main aspects of sustainability have to be covered, preferably without overlap.

Step 1.4: Set requirements for each criteria

After a final set of criteria are identified, the type of each criterion is determined, e.g. go/no-go, targets, or direct comparisons between concepts. Then targets or a basis for comparison for each criterion are developed. The aim is to develop a set of sustainability targets that can be re-used with only minimal modification for future development projects.

Step 2: Expand the conceptual design process to include definition of allowable design space

Before the search for solution starts, sustainability criteria and associated requirements are used together with the other domains of requirements and restraints. The domain representing sustainability criteria may aid by i) illuminating previously unexplored design space, and/or ii) further constraining the applicable design space to reduce the space that needs to be explored. Such a mapping of domains in a design space is principally illustrated in figure 3. This figure indicates areas (Design Domains) where we should search for solutions from different aspects. The figure shows that there is no unified area where all domains are united – initially it is not possible to find any design solution (concept) satisfying all views.

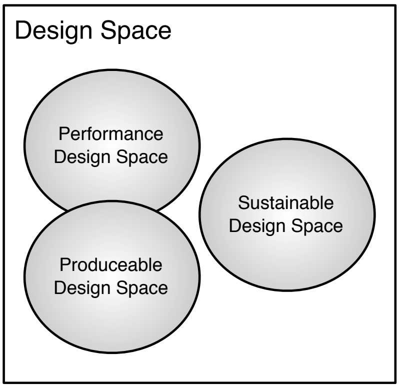

Figure 3. Principal map of design space within three domains.

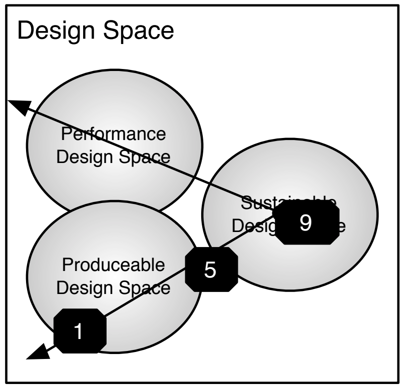

Figure 4. Compliance with sustainable criteria for design space elaboration

It is likely that the preferred, or even allowable, design spaces are not compliant so the designer's first task is to carefully understand the limitations and restraints of the given design pre-conditions. The designer can use the design space mapping as a way to understand limitations and opportunities in advance of actually identifying plausible concepts. Questions guiding the forthcoming design work can be formulated, such as "What would be necessary to merge these three design domains even more?" "What would be the consequence of violating one, or several, design domains?" "Can we modify the restraints and assumptions for the design domains to become more sustainable compliant?"

Then we introduce a Sustainability Compliance Index (SCI) to guide the search for solution areas direction. The SCI is currently suggested to be defined as a scale from 1 (minimal alignment) to 10 (complete alignment). This scale is in line with similar scale systems already established for grading maturity, such as TRL (Technology Readiness Levels). In the example, a tentative solution within the unified area between Performance and Produceability, may reach SCI=4 (only). The requirement may be "at least 5" as derived from sustainability criteria. See figure 4.

Step 3: Making Sustainability Criteria Assessment available in the design environment

As we progress into the actual search, identification and definition of conceptual solutions we start creating product information. Typically this is done using various design definition tools, such as CAD tools. It is highly desirable to bring the knowledge about sustainable requirements and criteria as close to the designers work environment as possible. Some requirements derived from sustainability principles in step 1 can be directly associated to the product model being defined, for example sustainability compliance of alternate materials. Such information can be made available through coloring the CAD model as materials are selected.

Secondly, guidelines and check lists for sustainability driven design can be made available directly via the designers interface with the product model being defined in the CAD tool. See figure 5. Functionality of the CAD system even allows certain requirements and rules to be executed immediately as the designer builds and modifies the conceptual design.

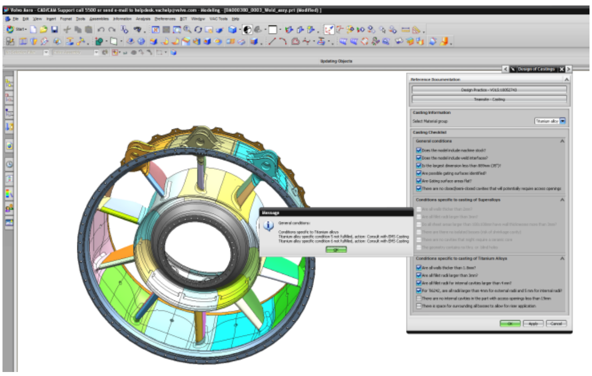

Figure 5. Illustration of making sustainability criteria assessment in a CAD model

Step 4: Ensure accessibility of data required to evaluate against sustainability criteria

When a set of conceptual designs have been defined, it is important that these can be evaluated against all applicable requirements. Data are necessary to make these evaluations, i.e. data that connect the decision to be taken with the sustainability criteria, e.g. material and energy flows relating to a selected material or process, upsteam supplier implications with regard to social sustainability, etc. There are two things to consider here. First, since sustainability criteria may require extensive amount- and quality- of data, the availability of data for the concepts is critical. Second, even if the necessary data exists, it may exist in many different sources. Practically, such data needs to be made available in the designer's context.

Illustrated by an example: a concept may use material A, which in turn can be manufactured in alternative ways. The material flow may not be known at first. It may, or may not, be recycled and reused. It may need to be treated in production in many ways that have not yet have been defined, etc. Consequently, criteria for sustainable evaluation within conceptual evaluation need to use data that already exist at that time, or can easily be derived. The evaluation criteria are therefore referred to as design criteria.

Step 5: Integrate sustainability criteria into the decision gate

The design and evaluation of conceptual solutions is a maturation process where the concepts as well as the evaluation methods are being refined and made more robust and detailed as the development process proceeds.

Since most companies use gated processes as a monitoring, control and communication mechanism during product development, the sustainability criteria, and acceptable level of the sustainability compliance index, can be implemented as gate criteria.

4 Application

A pilot test to identify a relevant list of sustainability criteria to be used in the very early phases of the product innovation process was conducted at the company Volvo Aero to get an indication of the applicability of the approach. Step 1.1 resulted in a long list of over 150 criteria based on eight different sources such as company requirements, ACARE, the environmental management system, and environmental impact assessments from previous development projects. Step 1.2, ensuring the full life cycle and socio-ecological perspectives, identified some additional criteria, frequently covering a more long-term time perspective. See illustration of the process in Figure 6.

The criteria were classified and grouped according to step 1.3. The full set of criteria need to be identified to be reduced according to the meta-criteria decided in the third step. However, in this simplified example the full set of criteria has not yet been identified. Despite being in process, the example shows how the criteria for tactical and strategic dimensions could support and guide decisions at the operational level so that solutions under development can act as flexible platforms in-line with the strategic direction towards more sustainable solutions.

5 Discussion

Products are often analyzed for some sustainability aspects in later phases of product design where changes may be quite costly to introduce. This research aims at filling these two gaps: bringing in a full global socio-ecological sustainability perspective, and doing so early and throughout the conceptual design process. Our ambition is to develop a decision support process that will guide the product developers in their daily work during development, evaluation and validation of concepts, technologies and decisions for future products and services. The results from a descriptive study formulated some guidance for sustainability criteria development that together with theories of basic principles for global socio-ecological sustainability build our first prescriptive approach for developing sustainability criteria and integrating them into a conceptual design process.

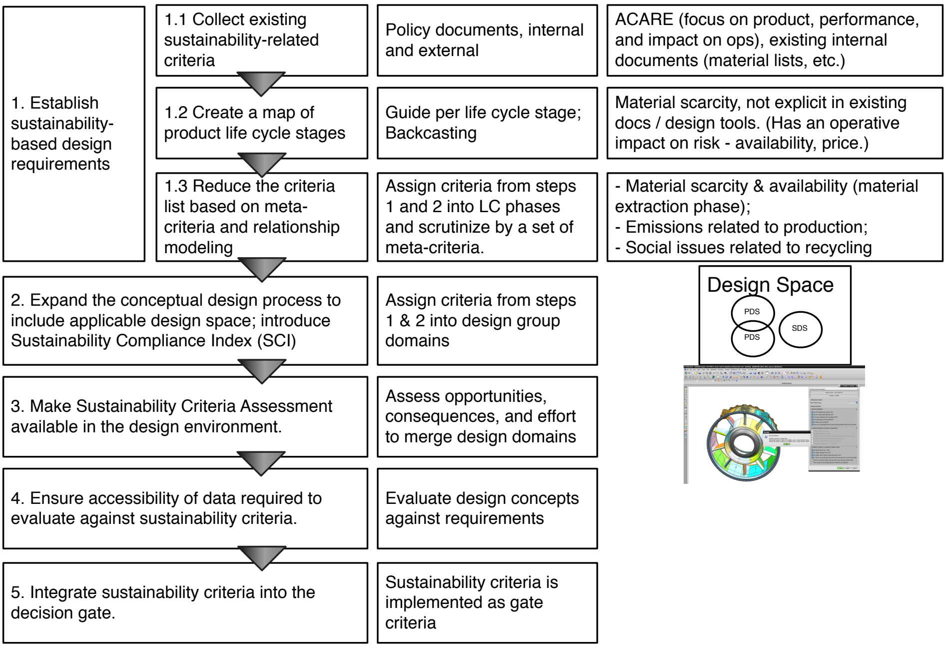

Figure 6. Introductory approach for Sustainability Integration in Conceptual Design

Initially we mention the need to consider three dimensions: operative; tactical; and strategic dimension, when integrating sustainability aspects in product design. The proposed approach does this at the strategic level by using basic principles that define the boundary conditions for a sustainable society, which is used to define the sustainability design space "set" (Step 1). Consideration of tactical aspects is included in Step 2 of the approach with regard to which level of the strategic sustainability design set would be integrated into the selective design solution of the design space measured through a Sustainability Compliance Index. Operative aspects for the designer then come in Steps 3-5 in order for sustainability aspects to be brought into the designer's desktop working environment (Step 3), appropriate data is available (Step 4), and decisions utilize the integrated and data-supported sustainability considerations (Step 5).

5.1 Observations

Establishing both comprehensive and operational sustainability-based criteria is imporant: a comprehensive and operational set of sustainability criteria can be derived with input from existing design requirements (Step 1.1) and complemented by both considering the product's full life cycle and utilizing a "backcasting from principles" perspective (Step 1.2). It is important that these criteria comply with a well-considered set of meta-criteria to ensure robustness (Step 1.3).

Sustainability-based criteria can be set independent of a design project: the overarching and multifaceted nature of sustainability suggest that the derivation of sustainability criteria can, and probably should, happen independent of and prior to the design process of a product. "Can" because at least the majority of sustainability criteria are not specific to the product itself, but rather to the relationship between any product and its surroundings (e.g. with regard to material use, emissions, etc.). "Should" because collecting sustainability requirements from the variety of sources from which they originate and aligning those requirements (next point) takes time to coordinate.

Criteria alignment through design cycle: it is critical that the criteria are aligned throughout the conceptual design cycle (not only integrated into the design requirements). By expanding our thinking from "get sustainability into design requirements" to "align sustainability criteria throughout the design cycle" we think there will be a much higher likelihood of influencing the sustainability aspects of the resulting products. Because having data and methods available to support processes requires time to be aligned with these criteria, we suggest that pre-defined criteria and requirements be made ready for implementation:

- Very early when design studies are being defined—this is a critical step to introduce the sustainability requirements and criteria as domains, both to introduce design opportunities and limitations as early as possible;
- By integrating with the designer's environment, making known data and methods easily accessible by the design engineer; and
- As gate criteria, with acceptance levels, in the company's development process.

Defining design space: Influenced by the concept of set-based concurrent engineering [Sobek 1999], efforts to integrate sustainability criteria into concept design processes would benefit from some modifications to the general design cycle introduced in Figure 1. Specifically, this means introducing sustainability as a design domain to be considered along with other design domains (e.g. produceability and performance) from the outset of the project. This would ensure that sustainability requirements are considered from the beginning, addressing the common challenge that sustainability aspects are considered after design decisions have already been taken. We have suggested the introduction of a sustainability compliance index as a means to introduce which direction to elaborate at this stage. Such an index can further be used for decision making.

Supporting designers with regard to the sustainability domain: there is a need to provide guiding tools for how to search for sustainable solutions that complement the sustainability criteria so that designers know how to work with those criteria

(Step 3). At a minimum this requires having appropriate data accessible, and likely implies a need for additional support tools.

Implications of introducing “Sustainable Design Space”: we think it is possible that introducing a sustainable design space as a domain, and a sustainability compliance index, may actually open up design spaces that have previously been disregarded because they were not at the intersection of existing (e.g. produceable and functional) domains. By introducing a third (sustainability) domain, this may encourage exploration of intersections between this and one of the other domains.

5.2 Further Research

This paper has primarily focused on establishing sustainability-based design requirements (step one) and including ideas for remaining steps. In further work, we will: i) continue to refine steps 2-5, and ii) test, validate, and continue to refine step one. The suggested approach needs to be verified in a concept design case to investigate if the sustainability criteria together with the suggested changes to the conceptual design process can guide decisions towards a more sustainable and long-term profitable solution for the company. This is planned for the next research phase.

6 Conclusion

This paper has proposed a 5-step approach for integrating sustainability into the conceptual design process that addresses two problems: 1) robustness of a “sustainable design space” in the same manner as the early steps in a set-based concurrent engineering approach, and 2) alignment of sustainability considerations throughout a generic design cycle. Initial work has been done to complete the first step in a design project to develop a set of robust sustainability criteria that ensure a full product life cycle perspective and a comprehensive view on social and ecological sustainability. Suggested next steps are presented that emphasize the need for alignment through all stages of the conceptual design process with an emphasis on defining applicable design space, searching for conceptual solutions, evaluating conceptual solutions, and deciding with regard to those conceptual solutions. In further work we will continue to develop and refine these additional steps more in detail and also test and verify the first step.

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